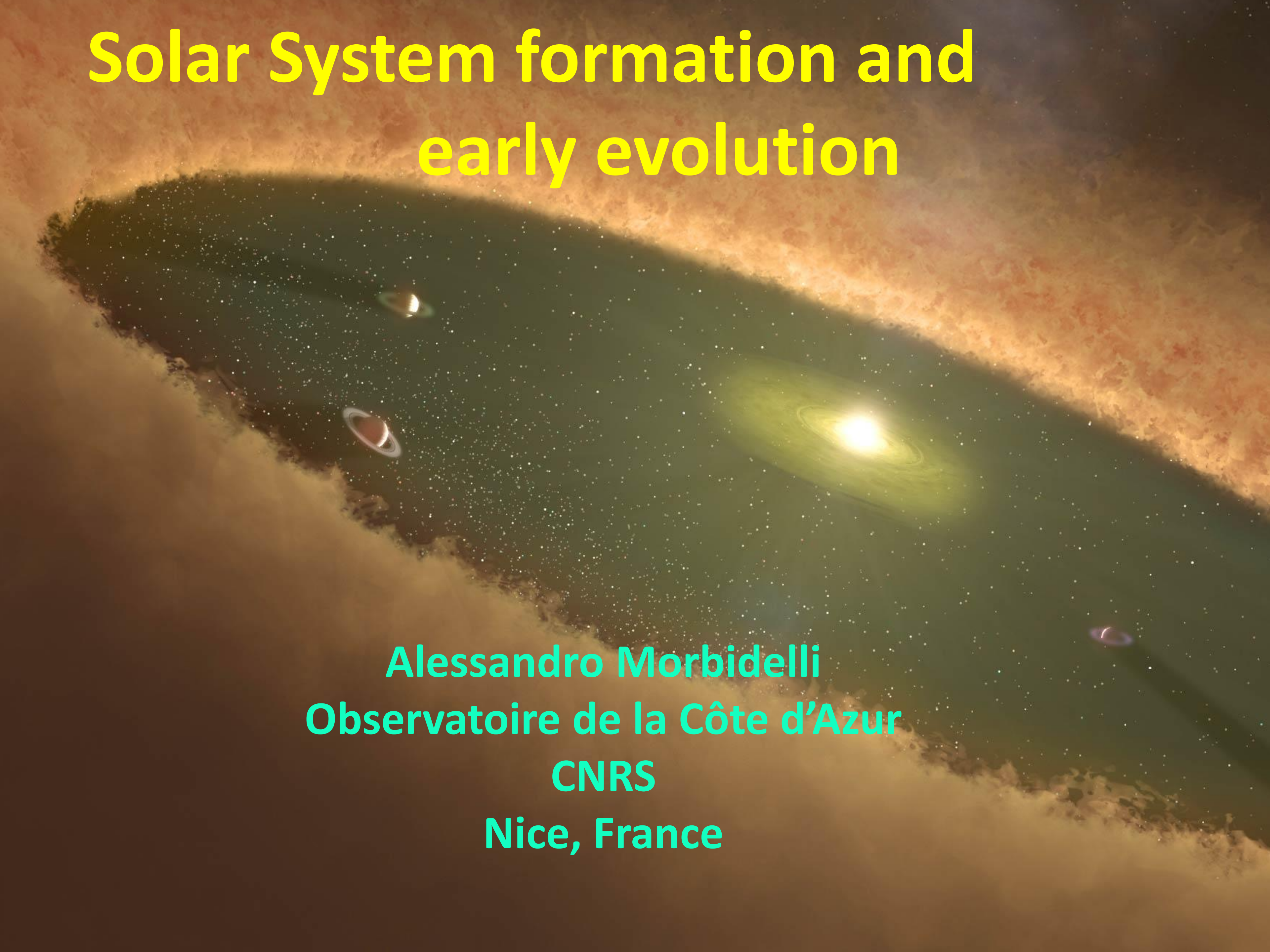
Solar System formation and early evolution



Alessandro Morbidelli
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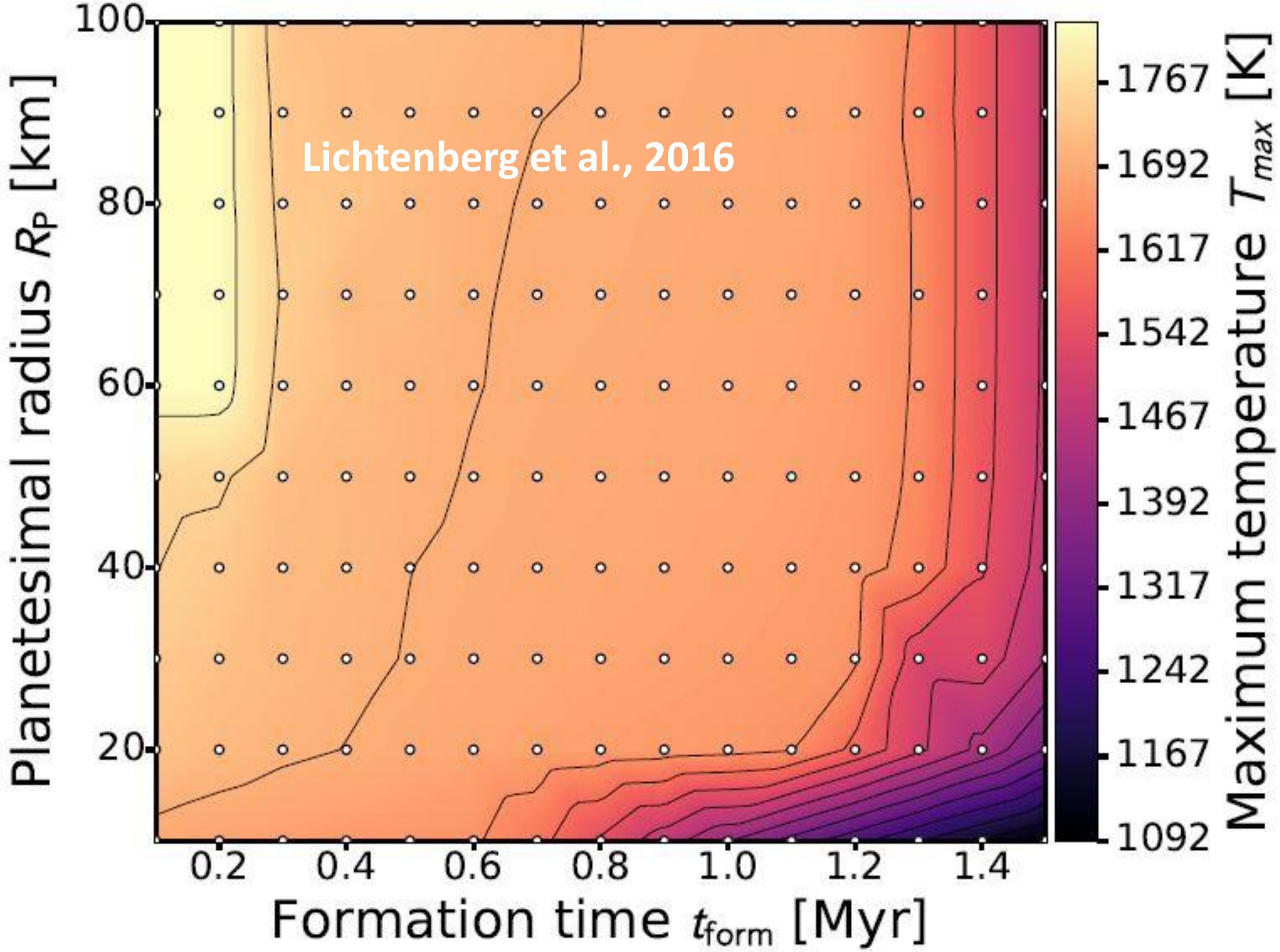
OUTLINE

Too vast subject, so I will focus on:

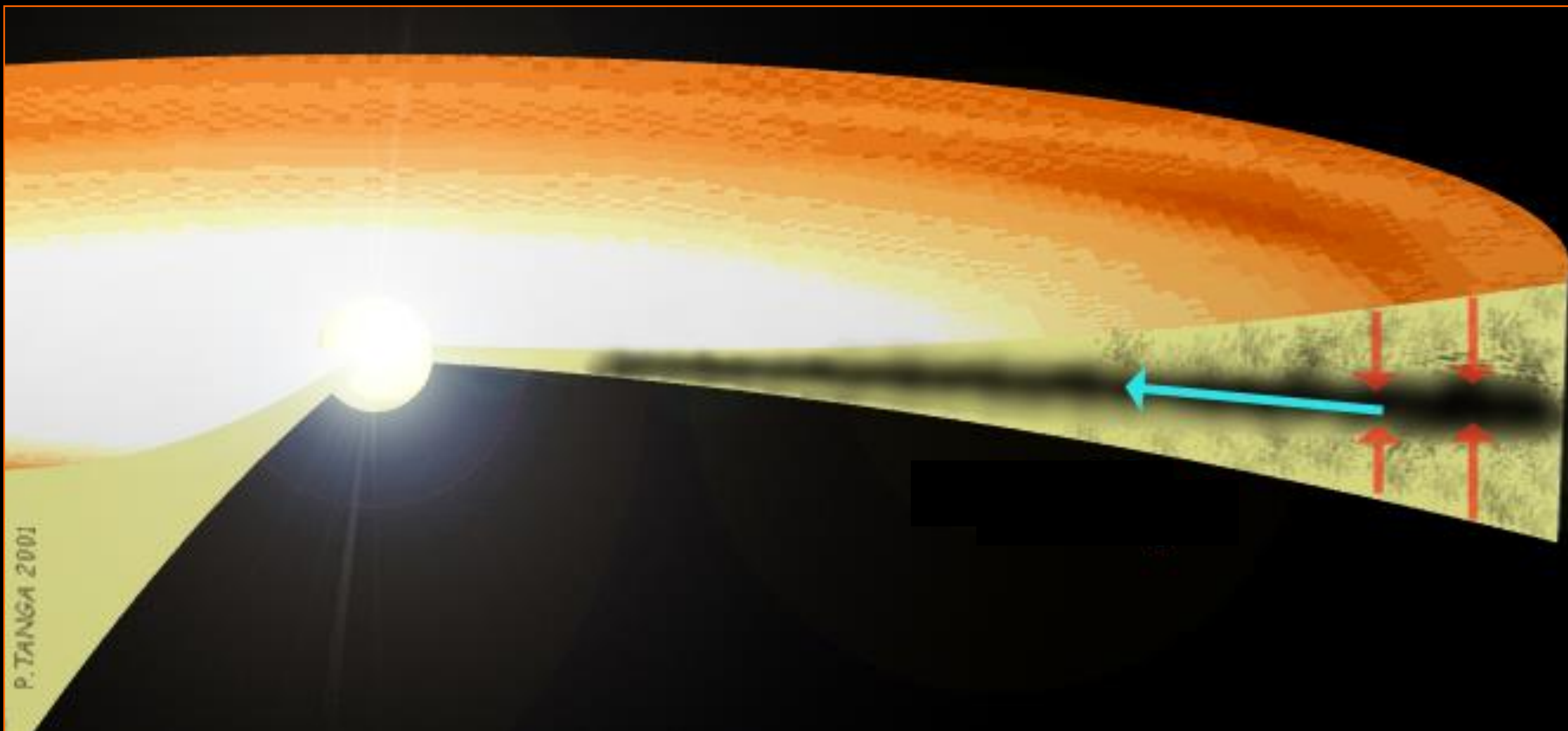
1. Primary accretion
2. Accretion chronology
3. Giant planet cores vs. planetary embryos
4. Circum-planetary disks and satellite accretion (again with emphasis on chronology)
5. Bonus: radial mixing of planetesimal populations

Why an emphasis on chronology of accretion?

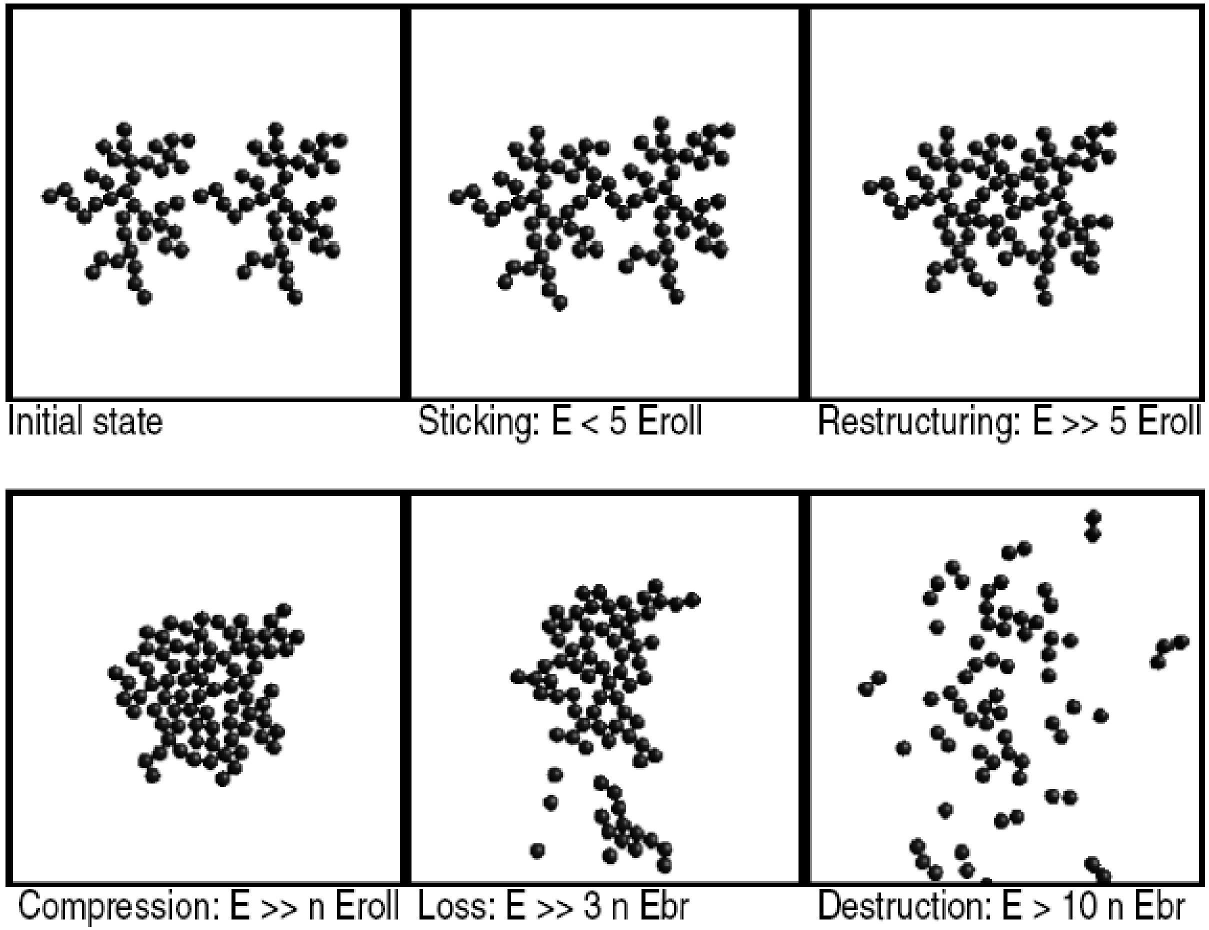


Because it determines the internal structure of a body, due to the heat released by short lived radio-nuclei

PLANETESIMAL FORMATION



Aggregate-aggregate collisions: results

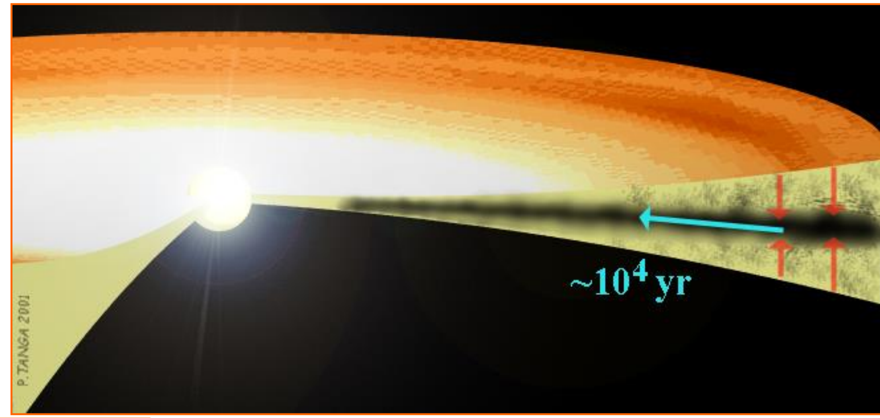


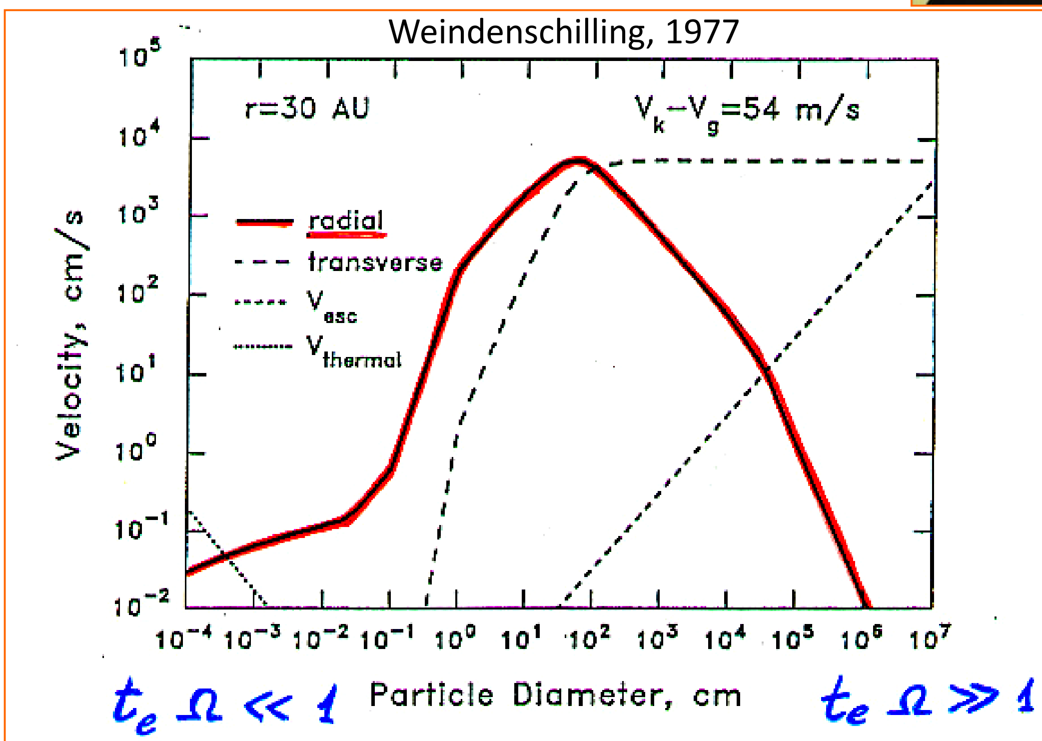
Dominik, Tielens (1997) – Wurm, Blum (2000)

Sunward dust fall

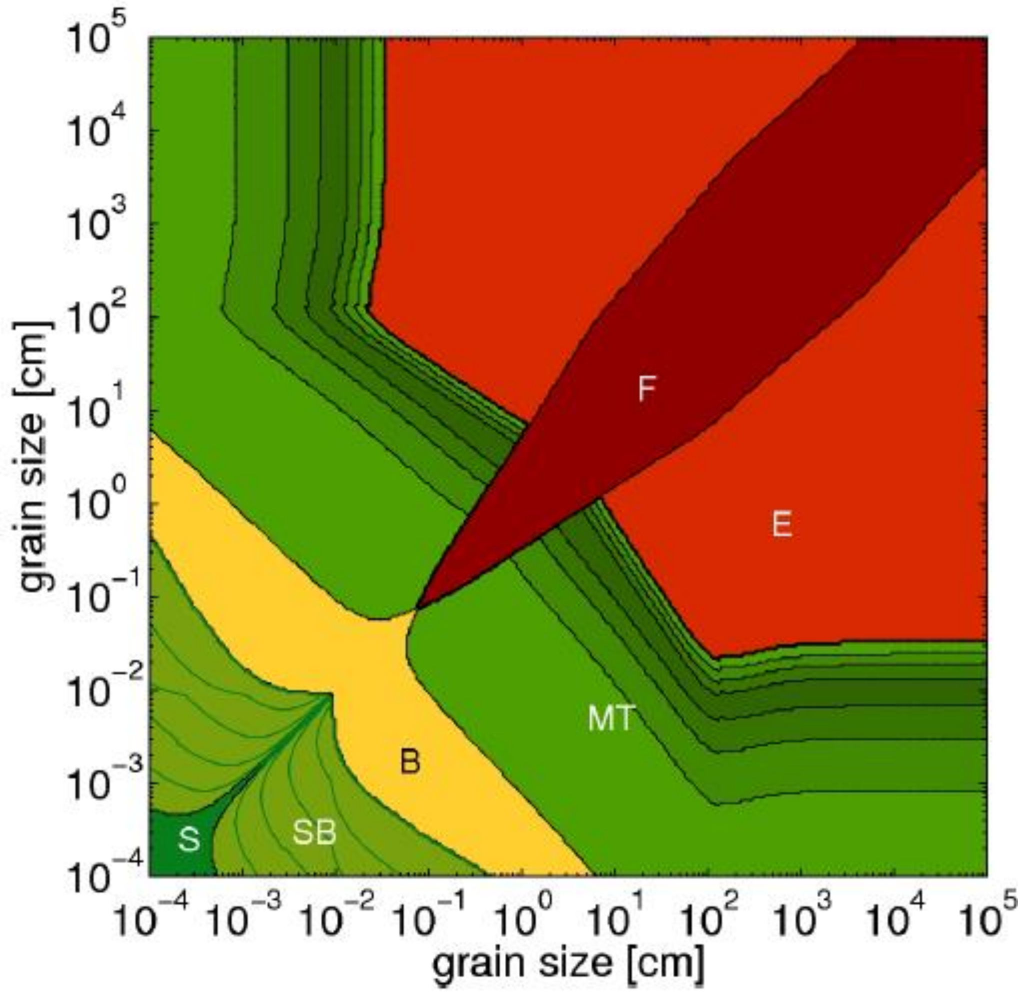
Dust particles run headwind
-> fast radial drift of m-size boulders

« meter-size barrier »





Accreting, bouncing, breaking…..



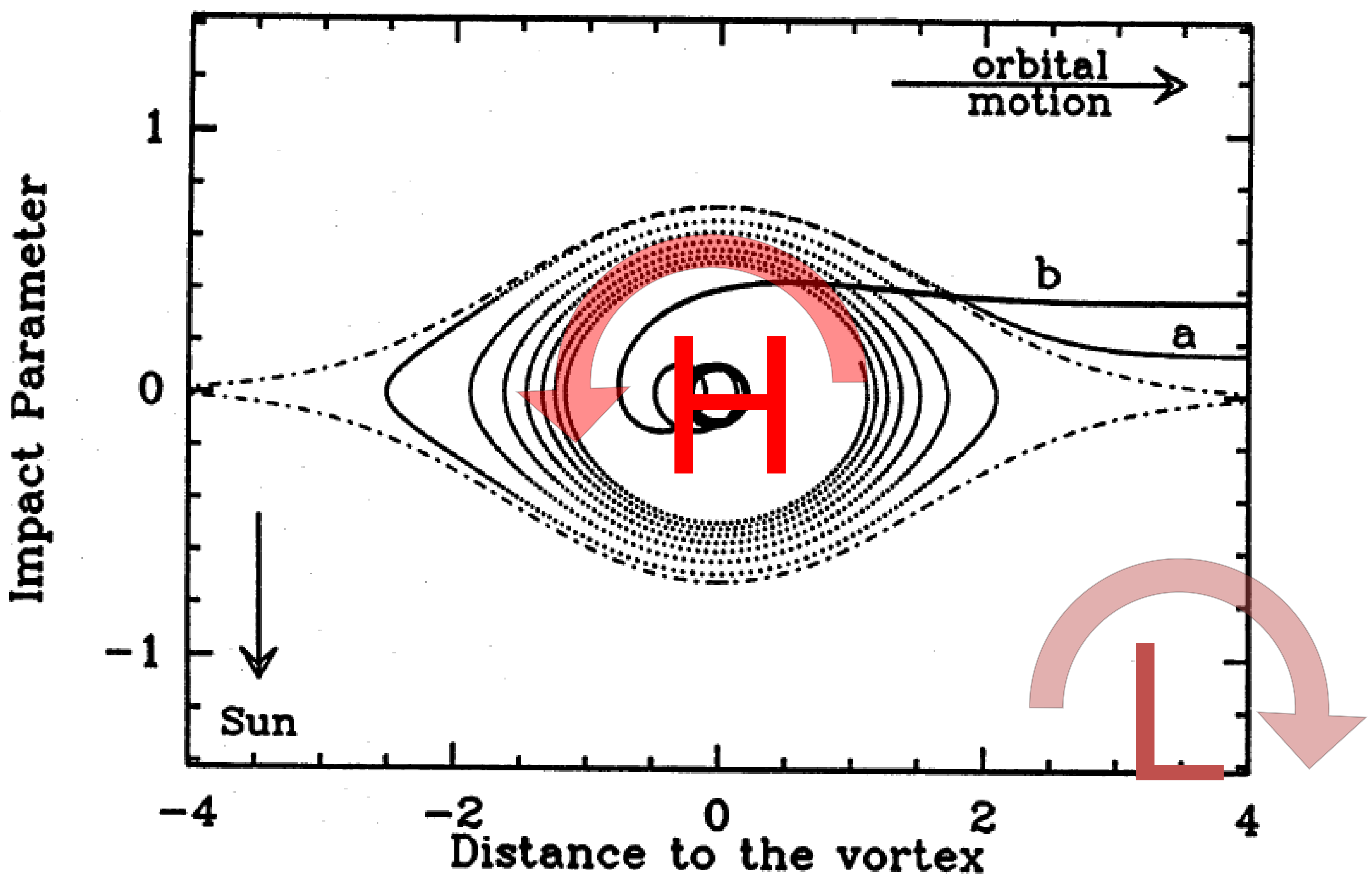
(Windmark et al. 2012)

A mm-size bouncing barrier for silicates

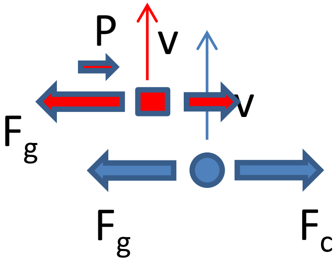
For icy particles, better sticking properties. Potential formation of fluffy aggregates (Okuzumi et al., 2012)

Turbulent disk: 10cm-1m particles are captured in vortices

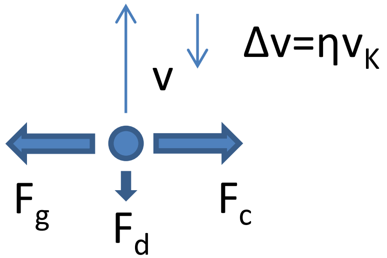
Disks are not thought any more to be very turbulent. Besides, to be trapped in vortices particles need to be much bigger than allowed by the bouncing barrier



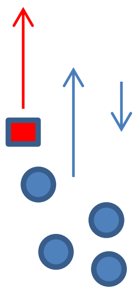
The streaming instability concept

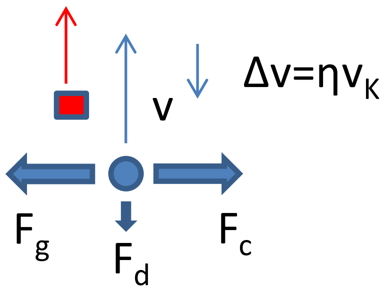


The streaming instability concept



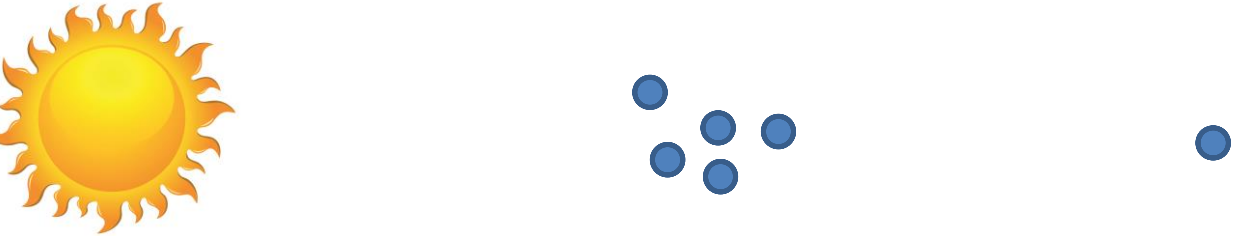
The streaming instability concept





The streaming instability concept

The streaming instability concept



Streaming instability (Youdin and Goodman, 2005) – spontaneous clumping of radially drifting particles

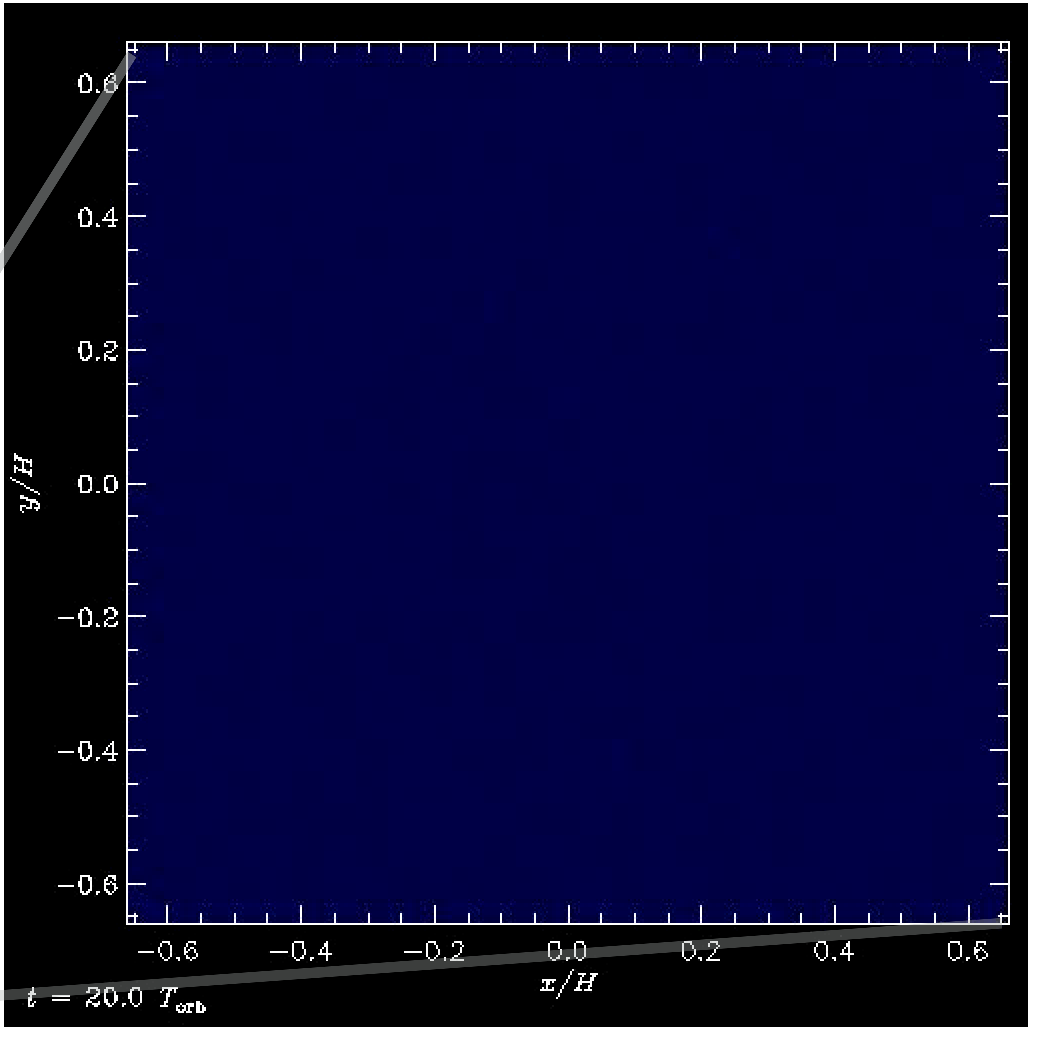
Johansen, Klahr, Henning, 2011

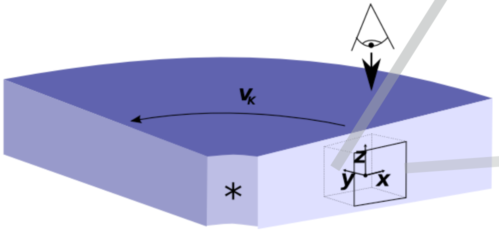
tau=1,Z=0.03,512^3

$$\dot{v}_{\mathrm{p}} = 1/t_f(v_{\mathrm{p}} - v_{\mathrm{gas}})$$

$$\tau_f = S_t = t_f\Omega$$

$$\tau_f = \frac{\rho_b R}{\rho_g c_s}\Omega$$

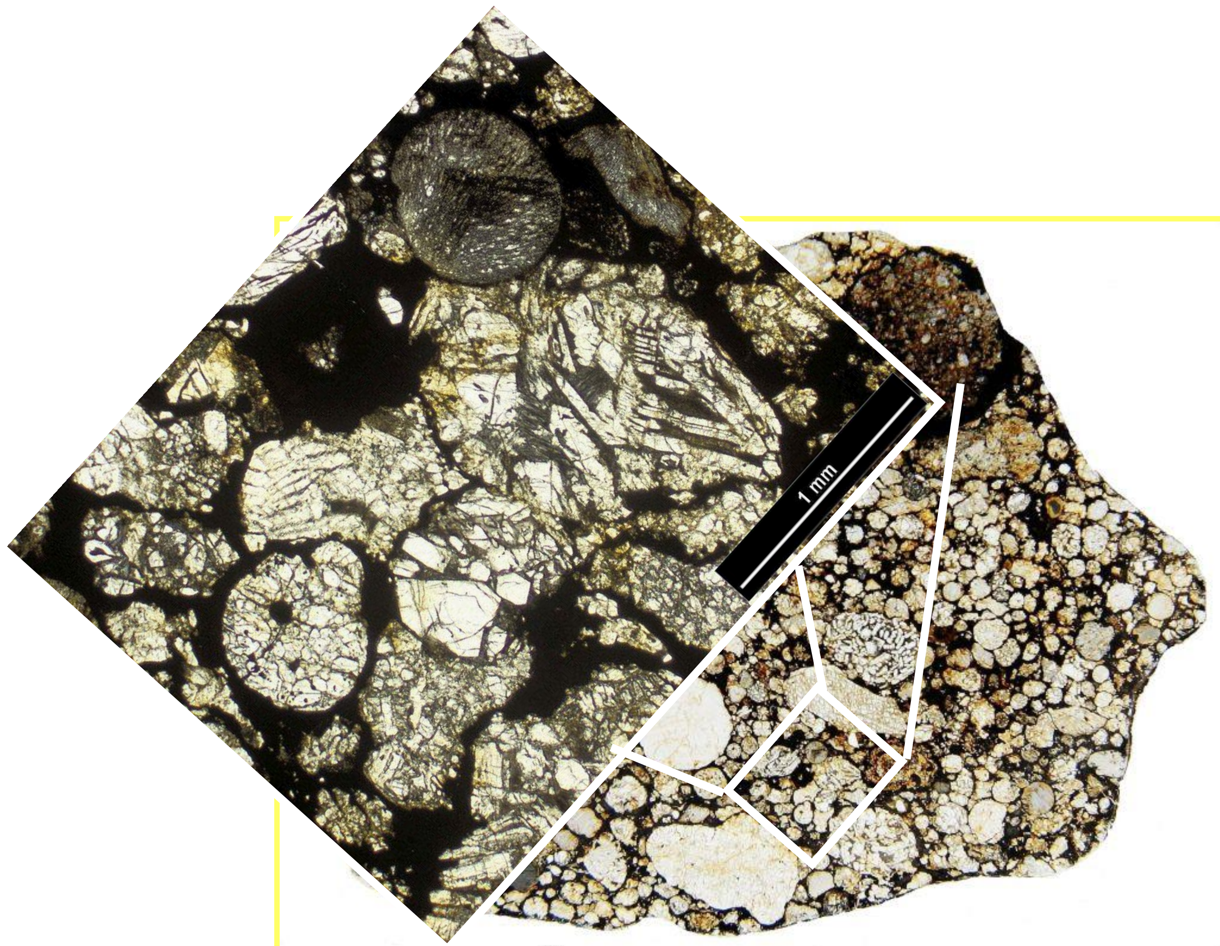




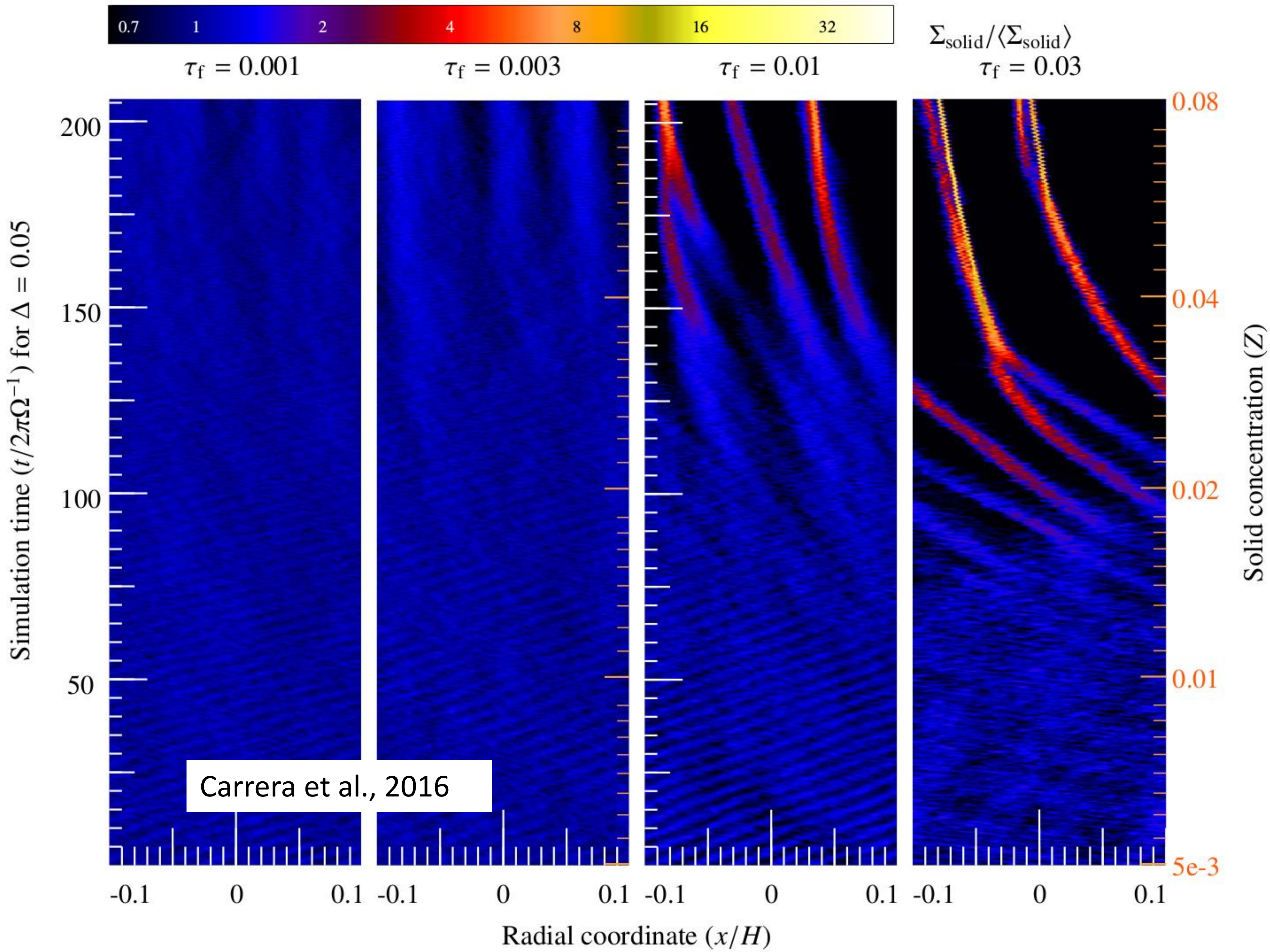
Problem: chondrites are made of sub-mm particles, not 15-60 cm “pebbles”
This is a problem to understand planetesimal formation in the inner disk (in the outer disk icy pebbles can be bigger and the Stokes number is bigger too)

Possibly, in high-density conditions, chondrules can collide with each other, avoid the bouncing barrier by multiple mutual collisions, stick to each other through their dust rims.
This way, they could form macroscopic aggregates, which may behave as previously seen

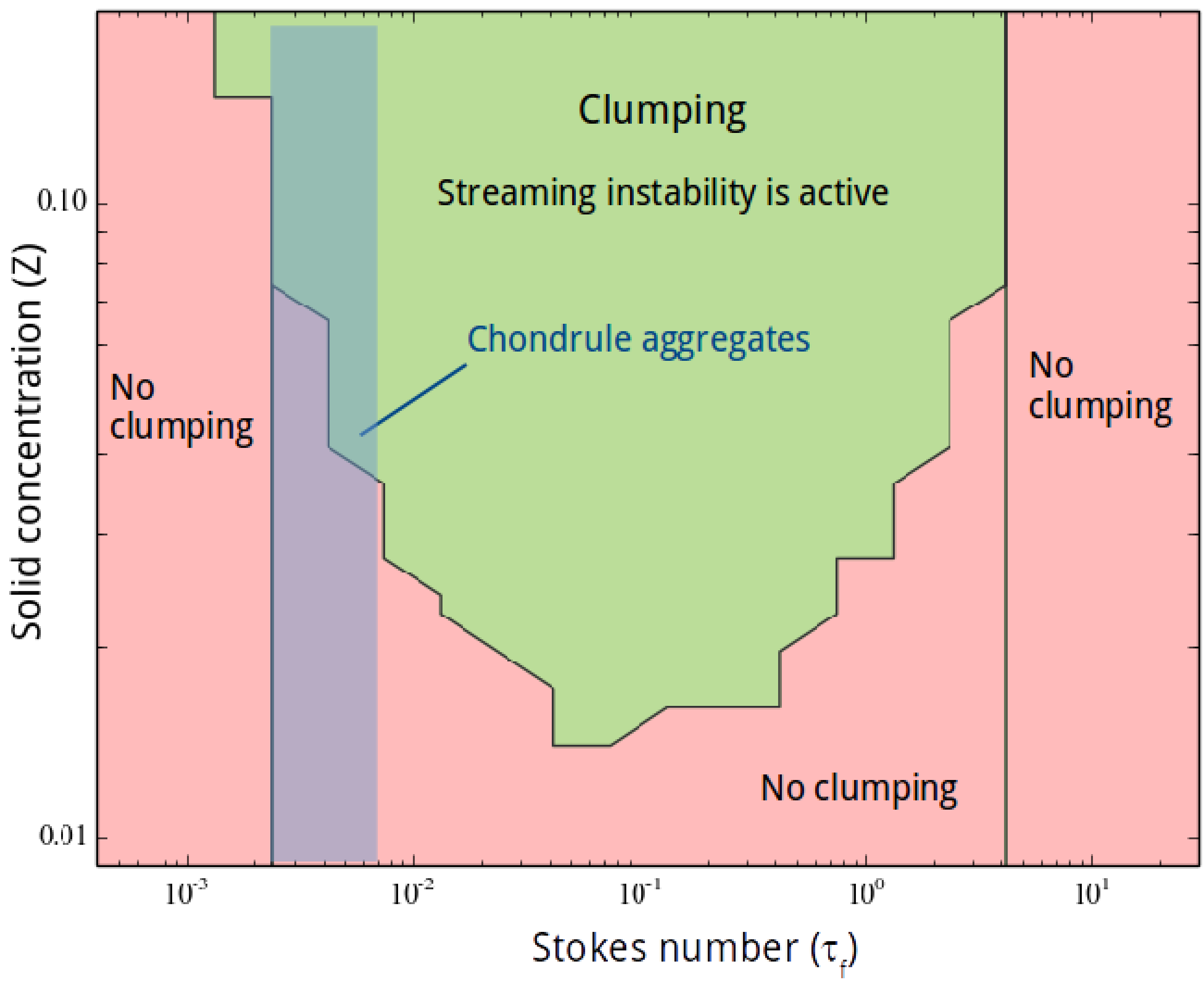
We do see cm-size chondrule clusters in chondrites!



Metzler et al., 2012



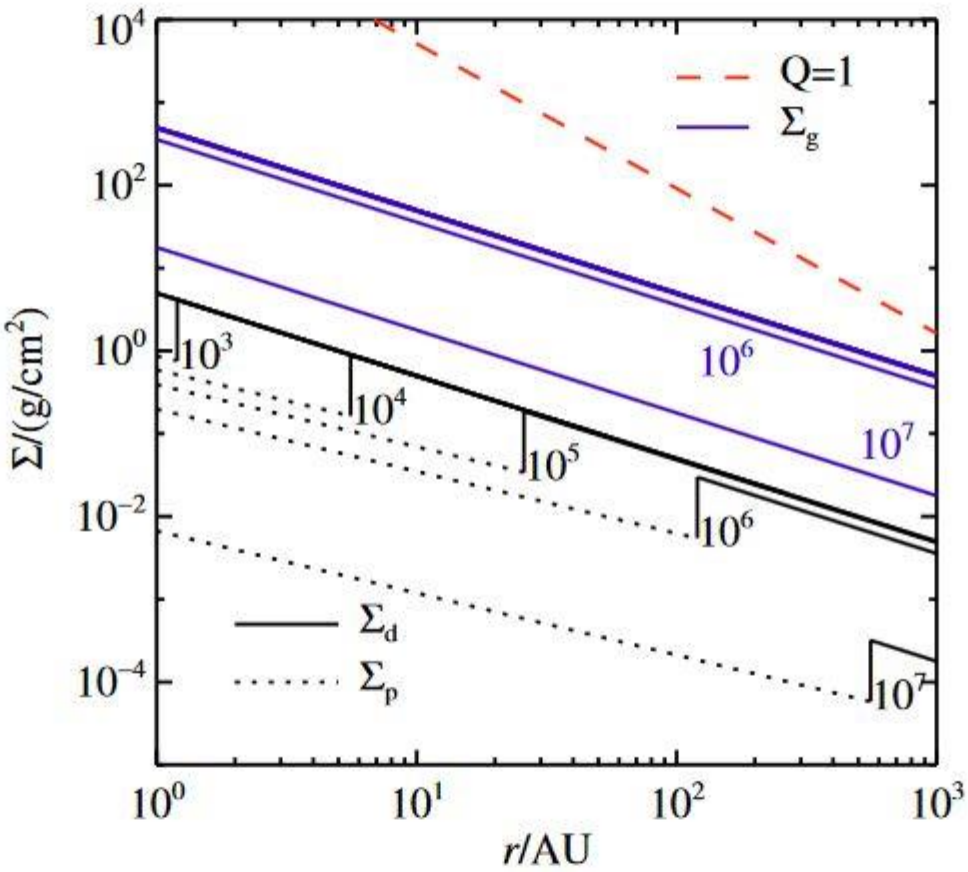
0.7
1
2
4
8
16
32
$\Sigma_{solid}/\langle\Sigma_{solid}\rangle$
$\tau_f = 0.001$
$\tau_f = 0.003$
$\tau_f = 0.01$
$\tau_f = 0.03$
200
150
100
50
Simulation time ($t/2\pi\Omega^{-1}$) for $\Delta = 0.05$
0.08
0.04
0.02
0.01
5e-3
Solid concentration (Z)
-0.1
0
0.1
Radial coordinate (x/H)
Carrera et al., 2016



Carrera et al., 2016

How to enhance the solid gas ratio?

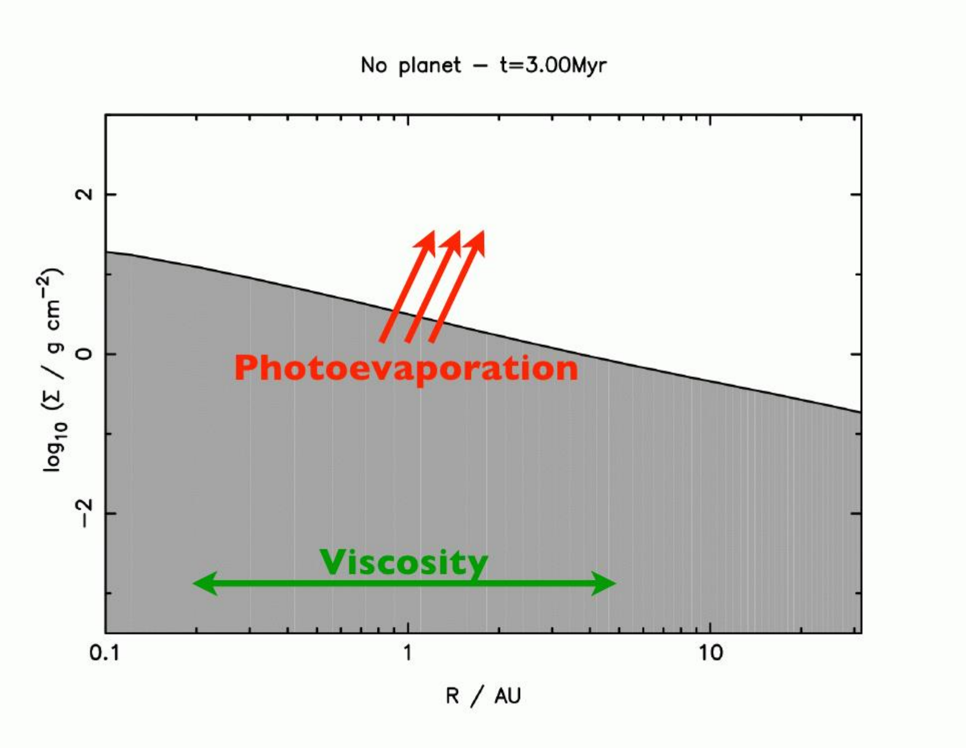
1) Deplete the gas and keep the solids



Gas depletion due to viscous accretion onto the star is slower than particle loss due to radial drift. Thus, the solid/gas ratio decreases with time rather than increase. Lambrechts and Johansen, 2014.

How to enhance the solid gas ratio?

1) Deplete the gas and keep the solids



Photoevaporation can remove gas faster than the timescale of particle radial drift.

How to enhance the solid gas ratio?

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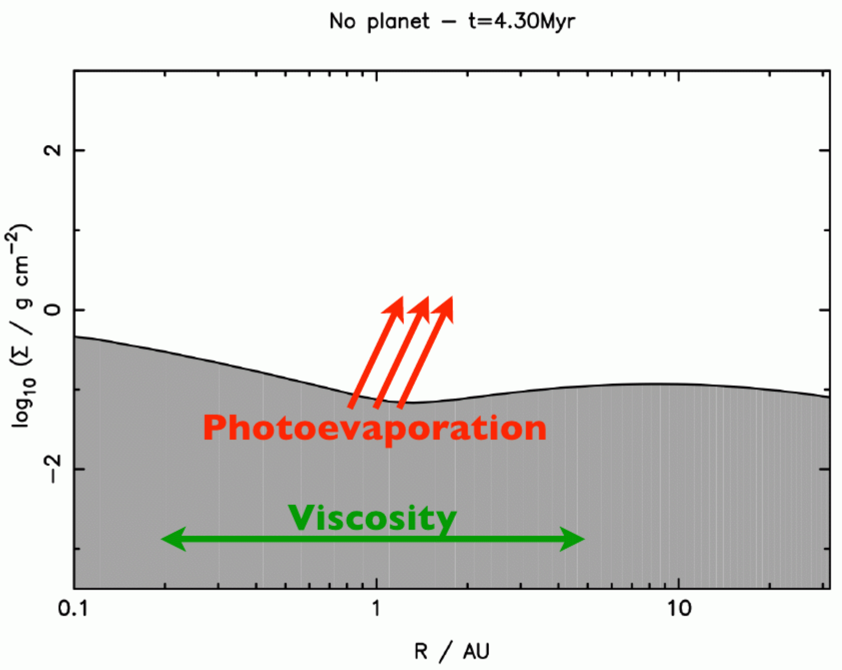

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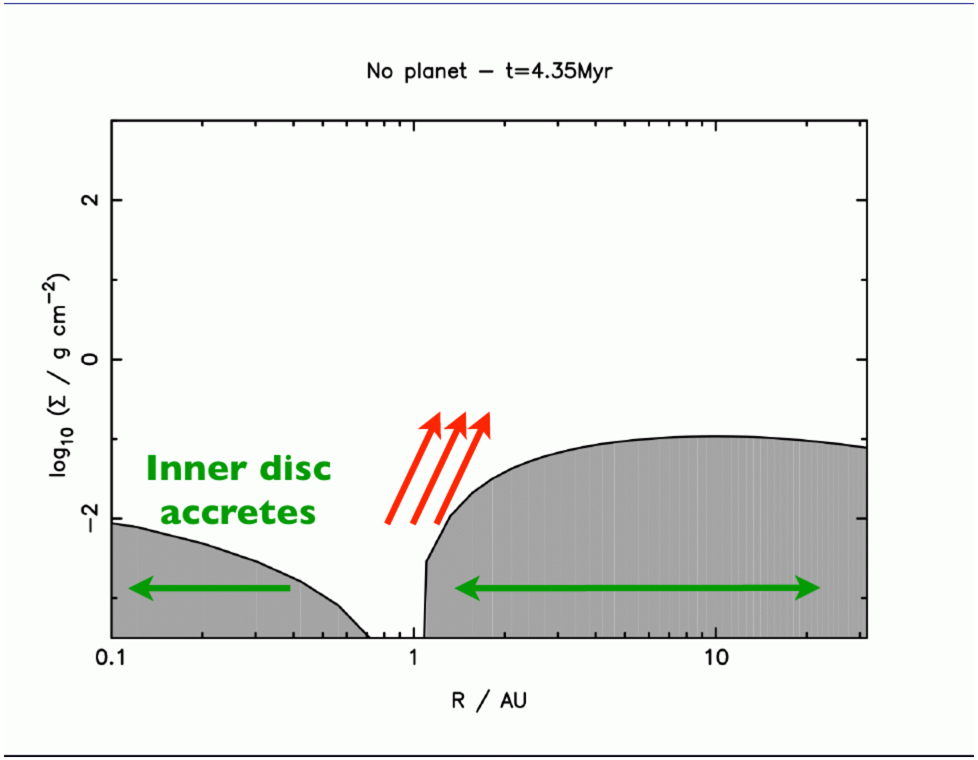
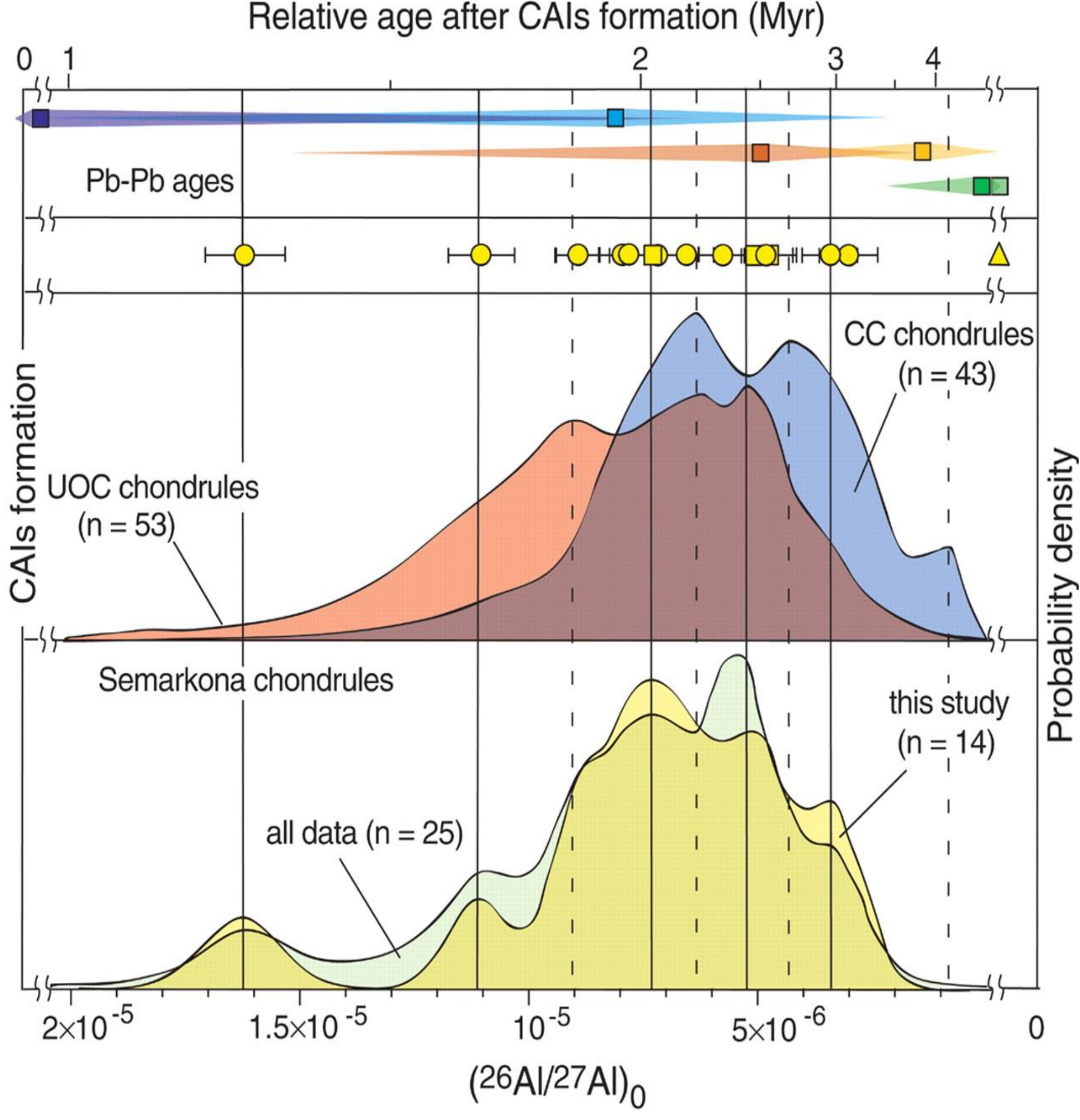


Photoevaporation can remove gas faster than the timescale of particle radial drift.

However, photoevaporation is effective only in the latest stages of a disk. So, this mechanism can only allow the formation of planetesimal by the streaming instability at a late time

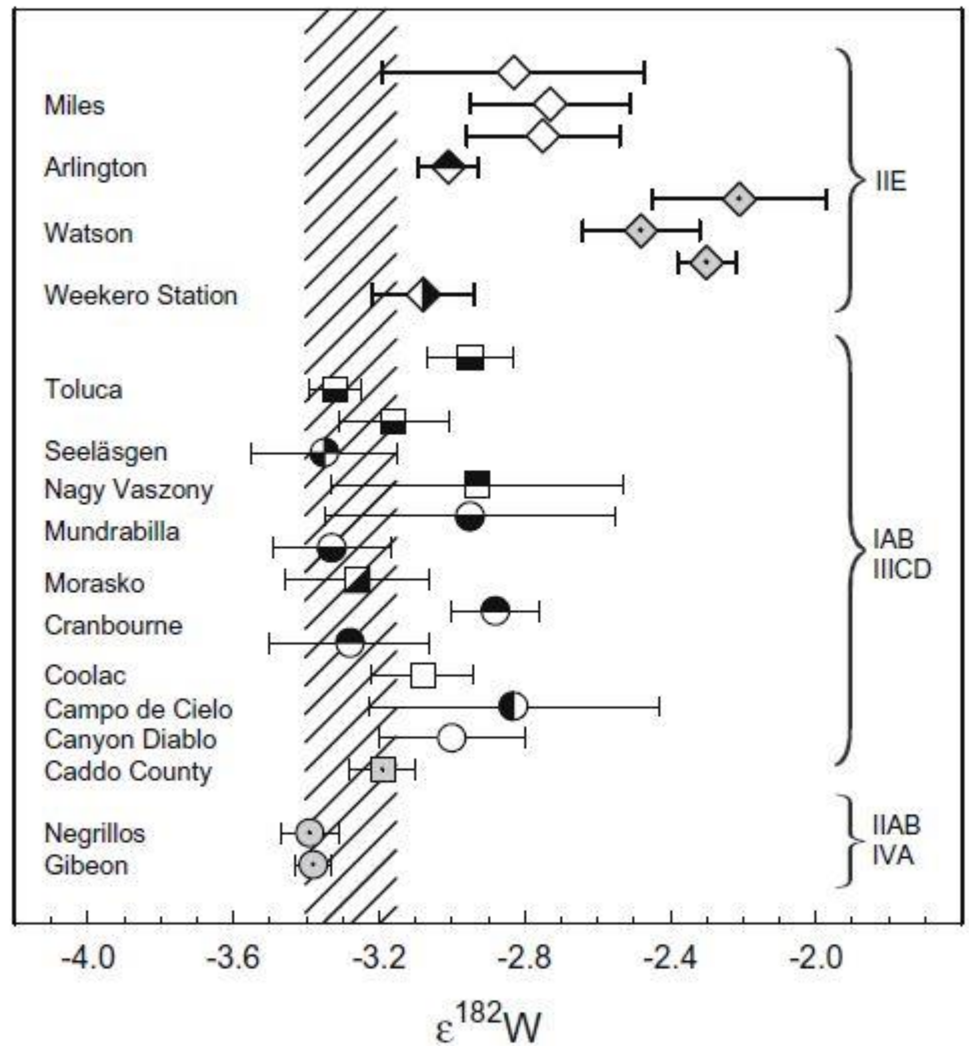
The parent bodies of chondrites (undifferentiated asteroids) indeed formed late, at 3-4 My, i.e. near the end of the disk lifetime



Villeneuve et al., 2009

Iron meteorites, however, come from planetesimals that accreted and differentiated very quickly, within 1 My at most

Kleine et al., 2009



How to enhance the solid gas ratio?

1) Pile-up by radial drift

$$\Sigma_{pb} = \dot{M}_F/(2\pi r v_r)$$

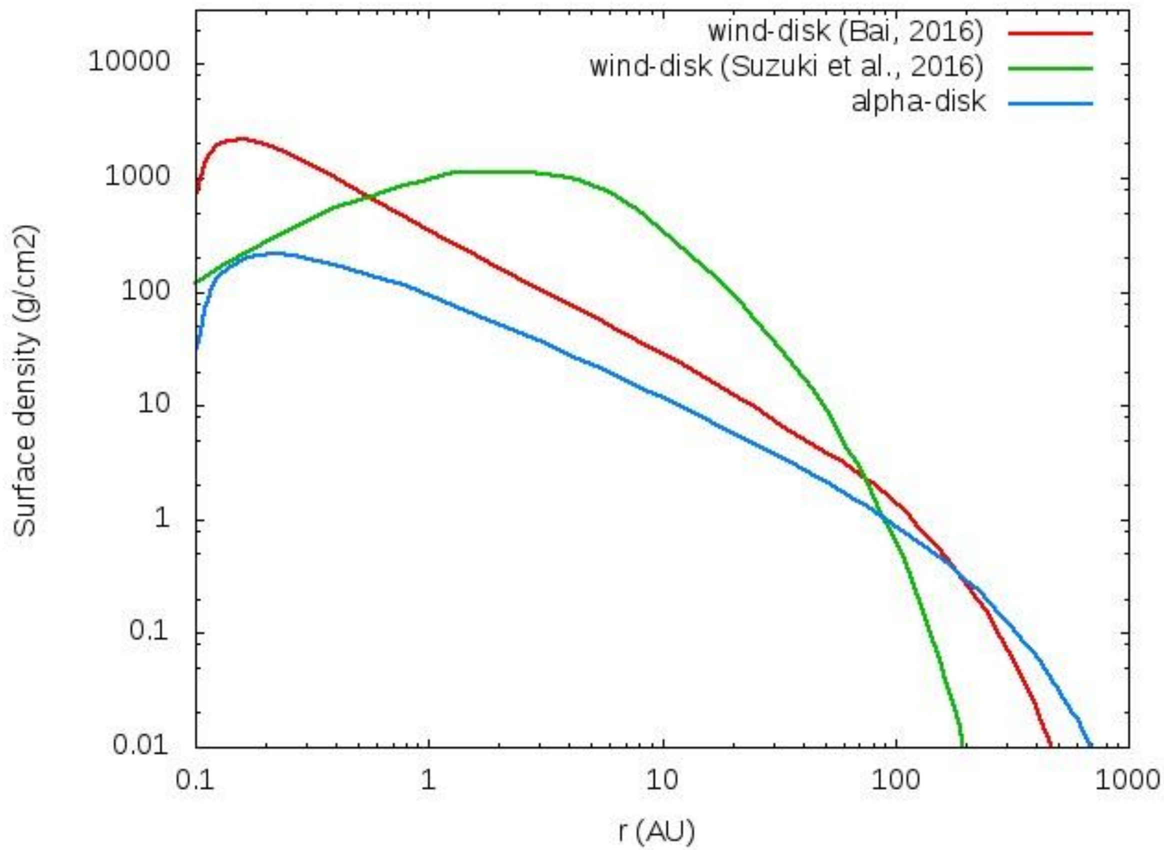
In order to have pile-up one needs that the term $1/rv_r$ increases faster than $1/r^\alpha$ for r-> 0, where $1/r^\alpha$ is the profile of the gas surface density

$$v_r = -2\frac{\tau_f}{\tau_f^2+1}\eta v_K + \frac{u_r}{\tau_f^2+1}$$

How to enhance the solid gas ratio?

1) Pile-up by radial drift

A first possibility is that η decreases somewhere in the disk (e.g. disk inner edge, outer edge of a cavity etc.



How to enhance the solid gas ratio?

1) Pile-up by radial drift

Even without edge effects, there is a moderate pile-up of pebbles in the inner part of the disk

η = constant in the inner part of the disk (where H ~ r)

$$\Sigma_{pb} = \dot{M}_F/(2\pi r v_r)$$

$$v_r = -2\frac{\tau_f}{\tau_f^2+1}\eta v_K + \frac{u_r}{\tau_f^2+1}$$

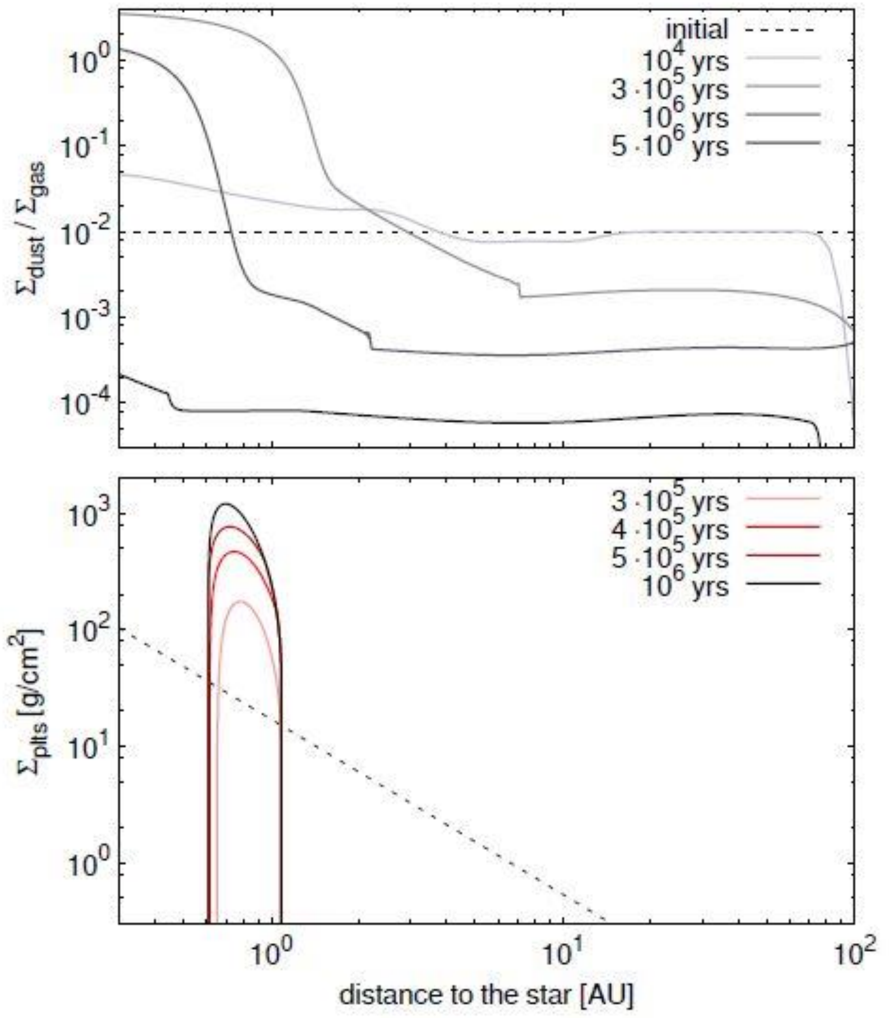
$$\tau_f = \frac{\rho_b R}{\rho_g c_s}\Omega$$ ~ r^{α}, where $1/r^{\alpha}$ is the profile of the gas surface density

Σ_{pb}/Σ_g ~ $1/r^{1/2}$

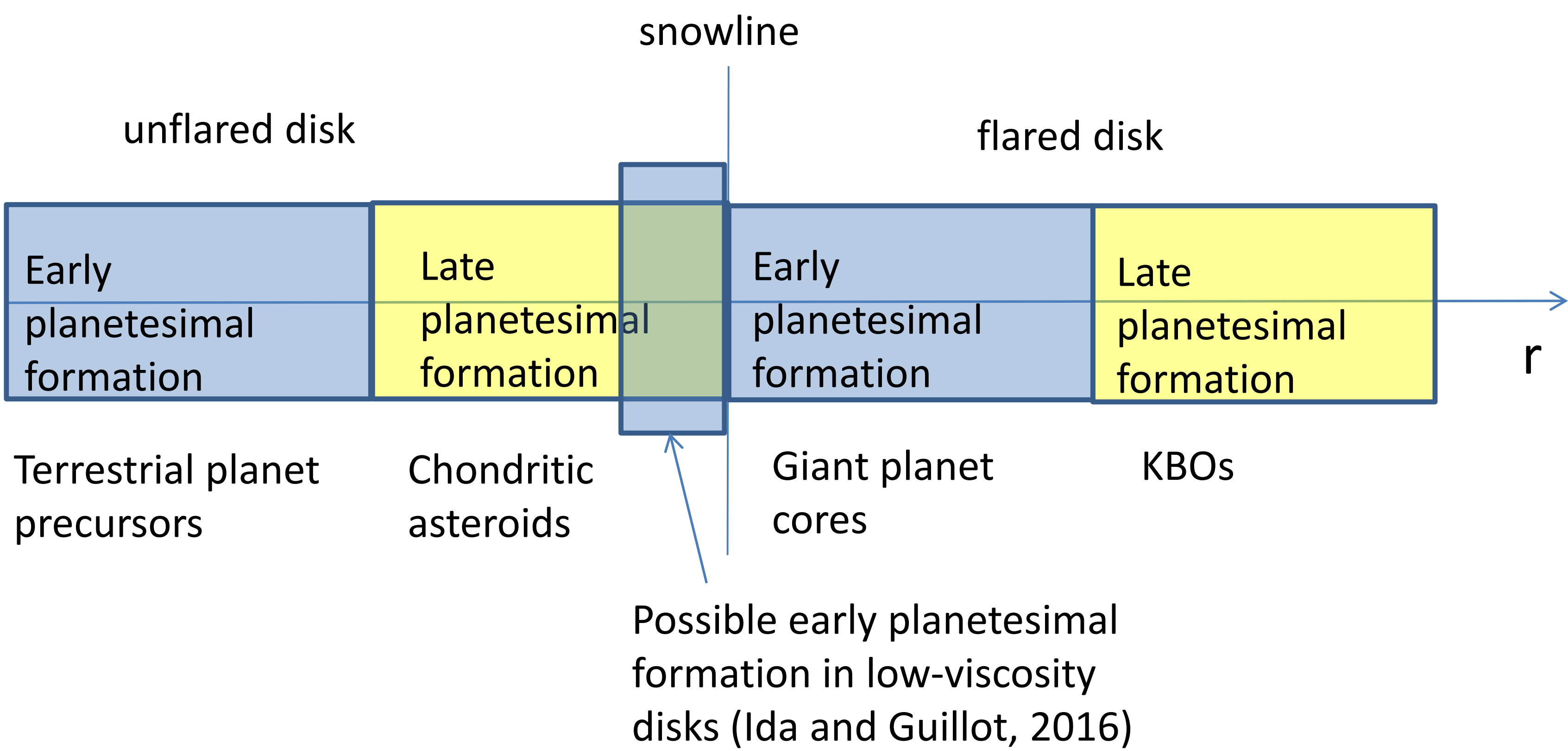
How to enhance the solid gas ratio?

1) Pile-up by radial drift

Drazkowska et al., 2016



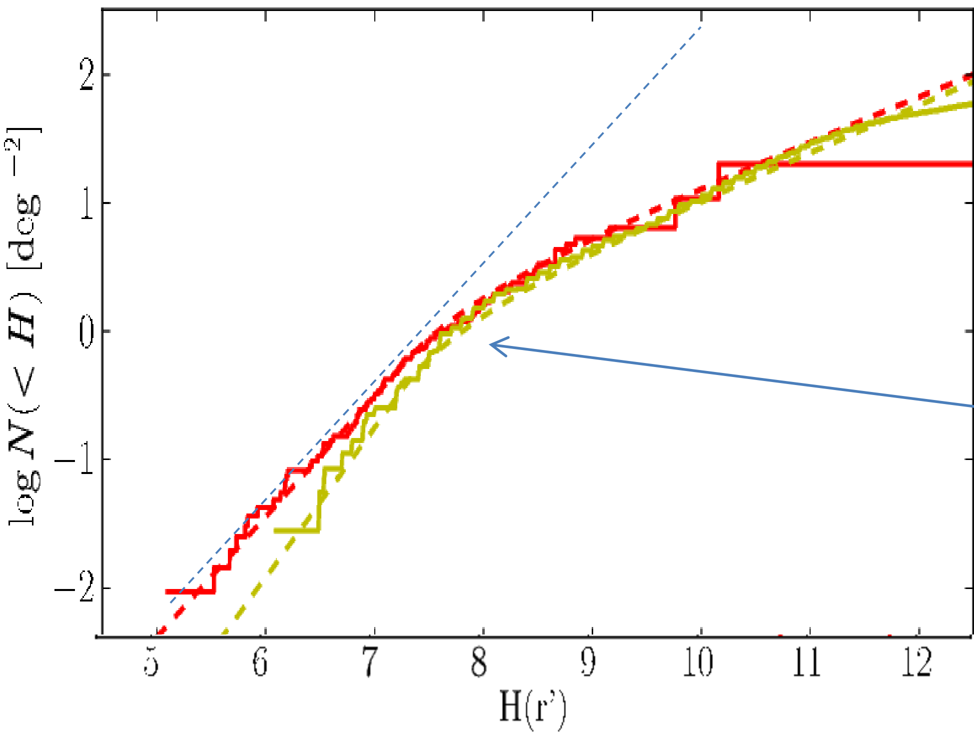
Thus, in principle one can expect a situation like this.....

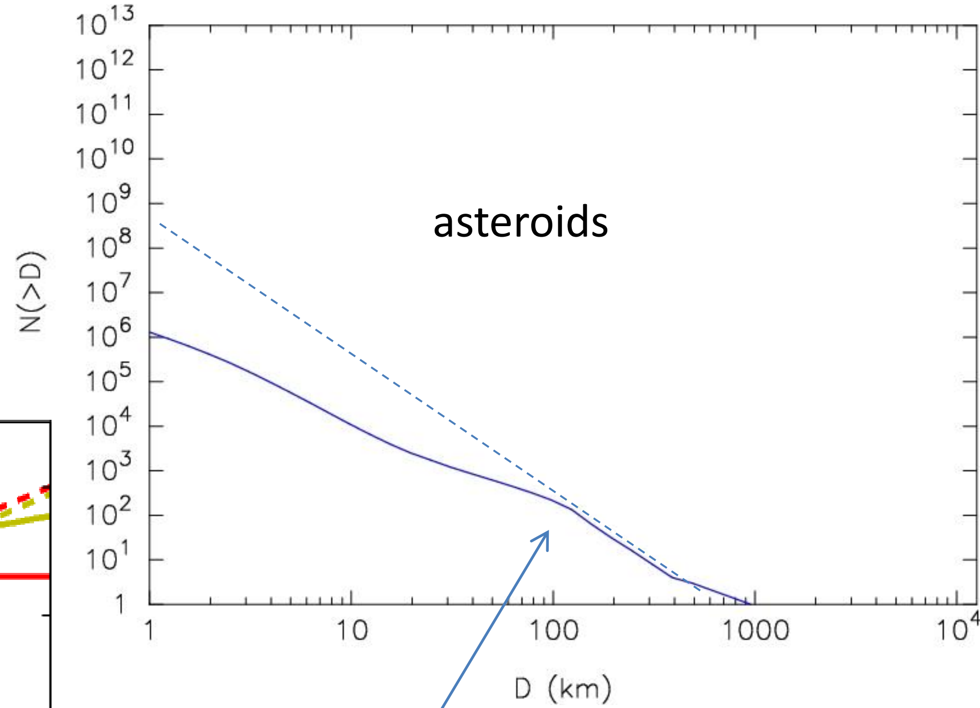


Planetesimals formed big., with a preferential diameter of ~100Km

$$a_c = \frac{H/R}{0.04}\sqrt{\frac{\delta}{2.7\cdot 10^{-6}}}\sqrt{\frac{0.1}{\mathrm{St}}}\,98\mathrm{km}.$$

Planetesimal size formula from SI theory (Klahr et al., submitted)





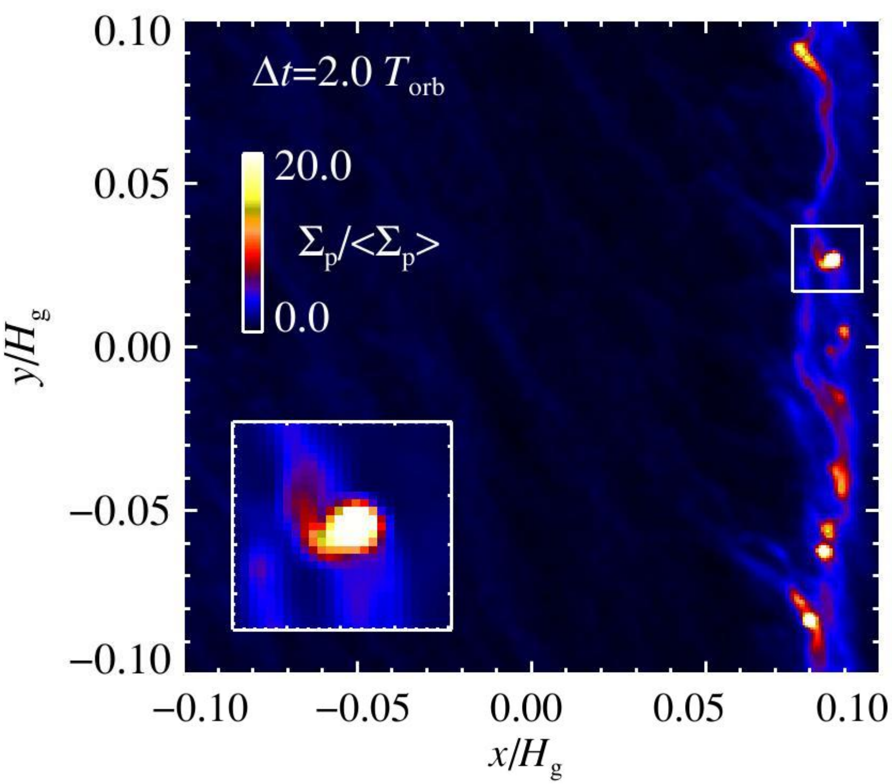
Primordial `bumps

From planetesimals to proto-planets

Once the first planetesimals are formed they still reside in a disk of gas and pebbles.

Thus they can still accrete pebbles flowing by them in the disk

"Pebble accretion process" (Johansen and lacerda, 2010; Ormel and Klahr, 2010; Murray-Clay et al., 2011; Lambrechts and Johansen, 2012)



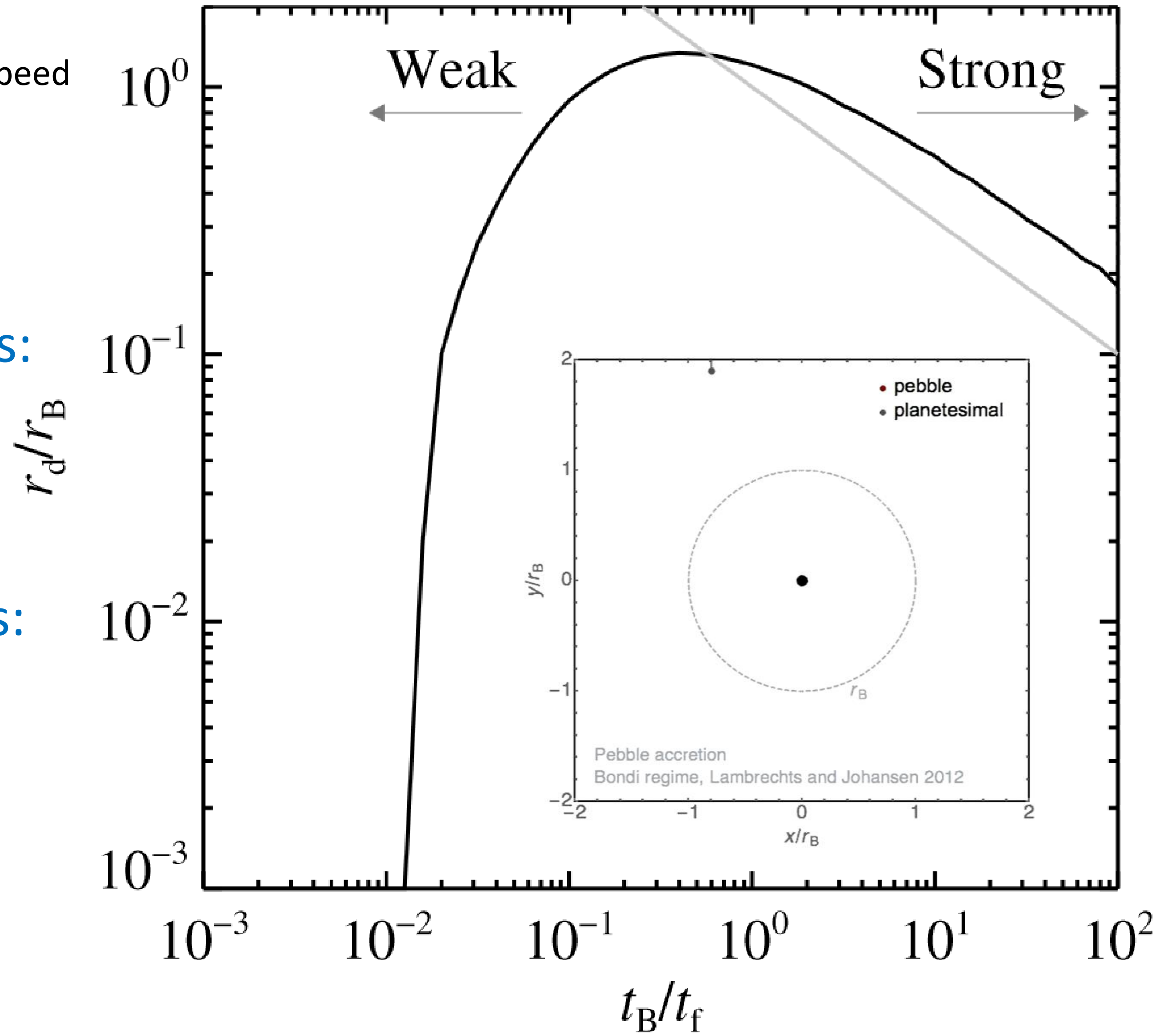
Pebble accretion

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

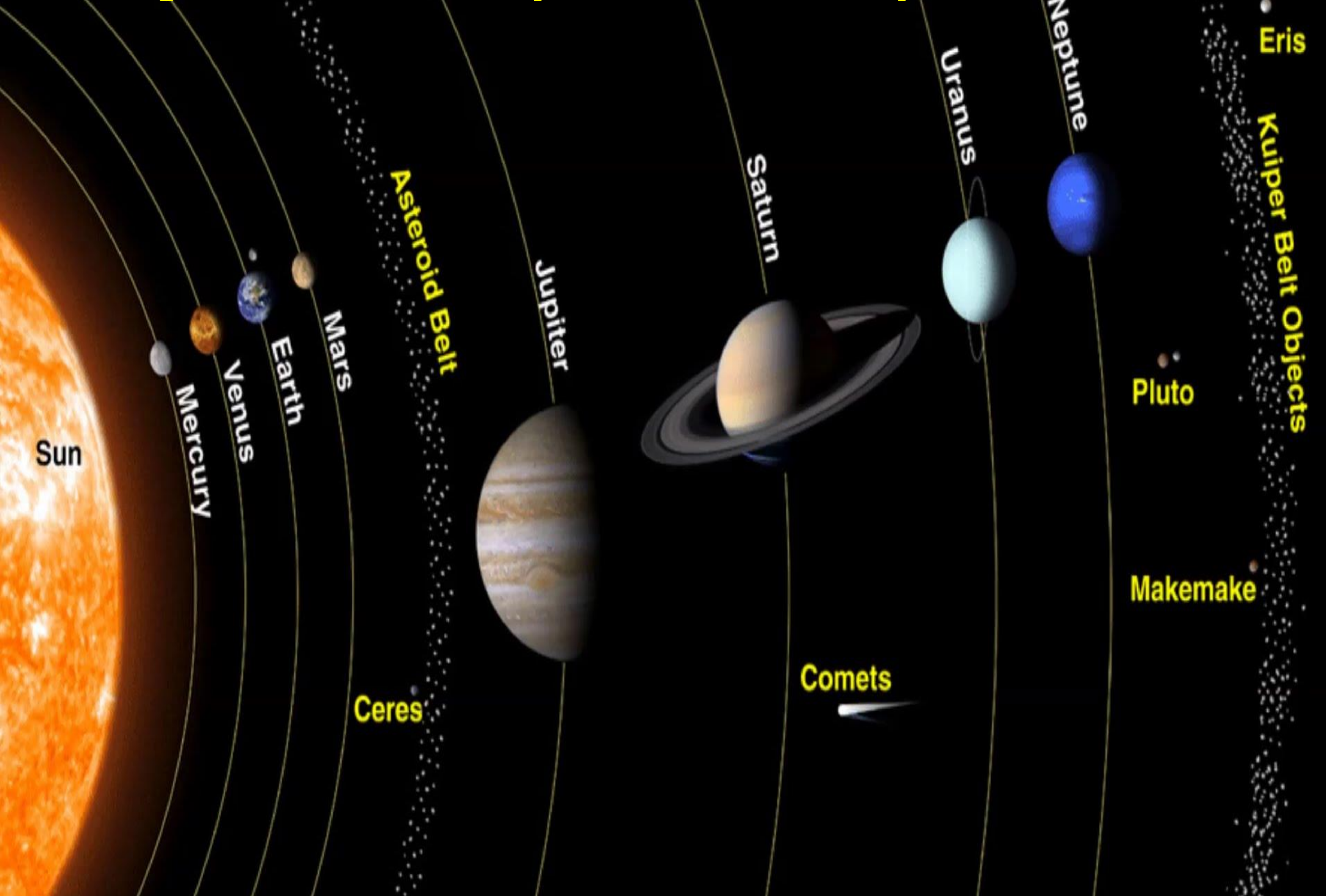
headwind speed

For small planetesimals:
1/M d*M*/dt ~ *M*;
(runaway-growth)

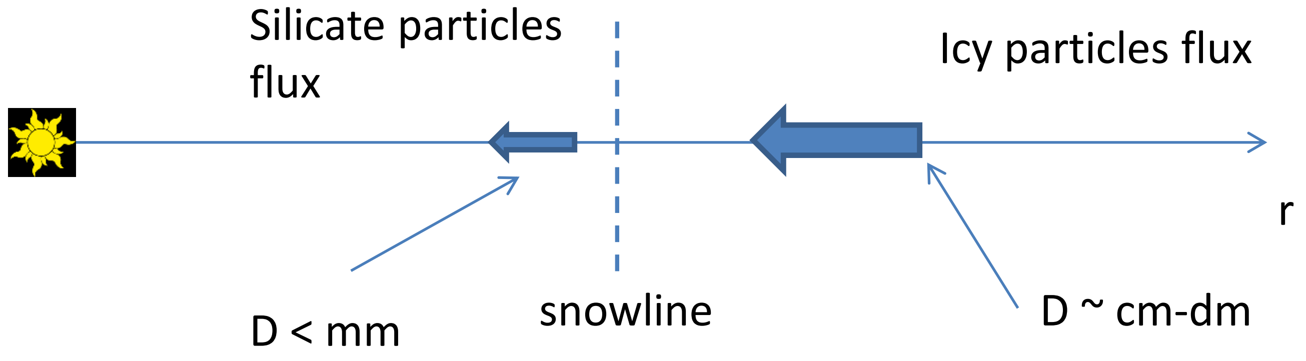
For large planetesimals:
1/M d*M*/dt ~ *M*$^{-1/3}$
(oligarchic-growth)



The great dichotomy of the Solar System



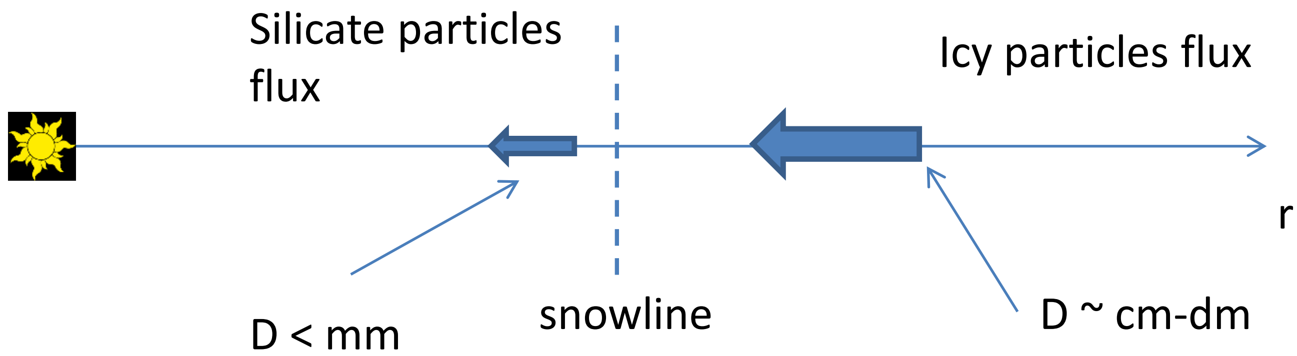
This could be due to different planetesimla sizes on different sides of the snowline, or to different efficiencies of PA



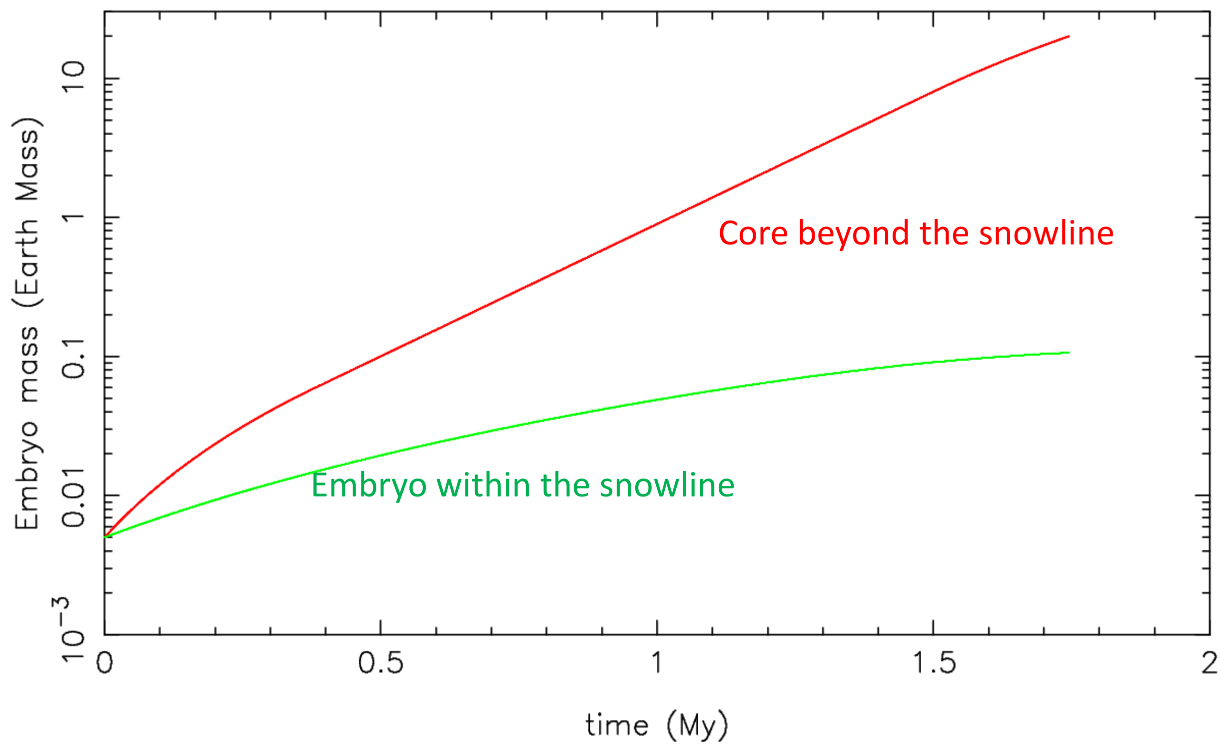
Assume:

- A mass-flux that decreases by a factor ~2 at the snowline
- An order of magnitude change in particle size (this could be due to the disintegration of dirty-icy pebbles into a collection of silicate grains due to ice sublimation (Morbidelli et al., 2015) or to a change of collisional regime (Banzatti et al., 2016)

IDEA

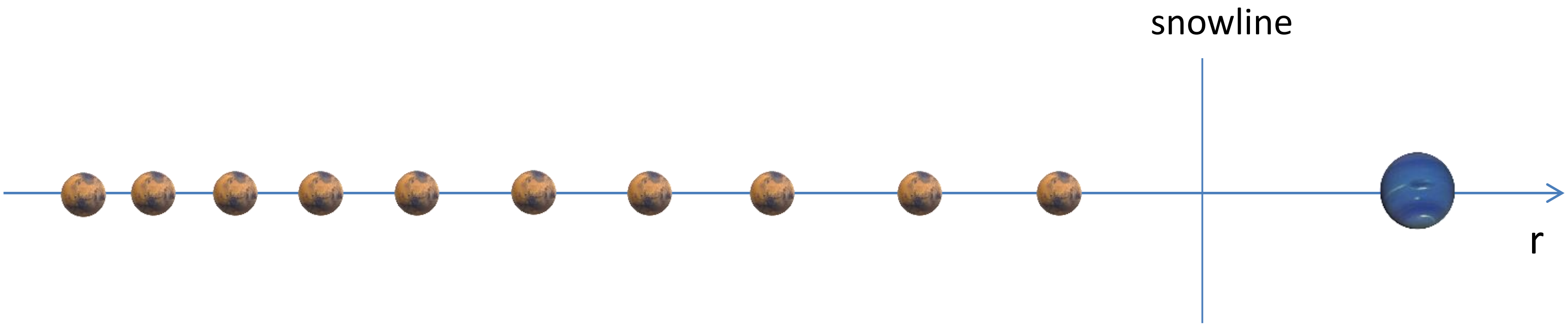


If the small particle layer is thick enough so that their accretion is a 3D process, then smaller particles are more difficult to accrete.
From $H_p=H_g(\alpha/\tau)^{1/2}$
this requires α~10^{-5}



Morbidelli, Lambrechts, Bitsch and Jacobson, Icarus (2015)

This should be the generic initial structure of a planetary system….



Consistent with the structure of the Solar System, but not with the existence of hot super-Earth systems around most of the stars

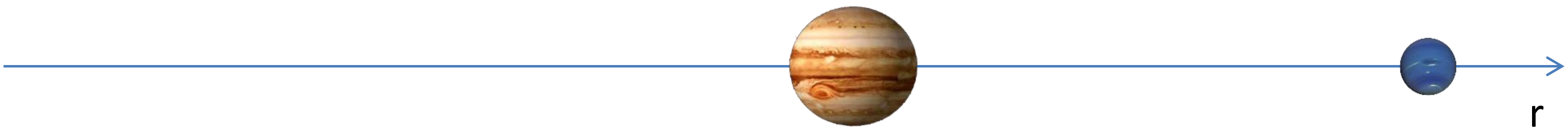
MIGRATION is the key!!

We may conceive the following scenario:

If the outer disk produces only super-Earth mass objects, they migrate into the inner disk

We may conceive the following scenario:

If the innermost SE manages to grow to a giant planet, its migration is slowed down and it retains the other super-Earth(s) behind it

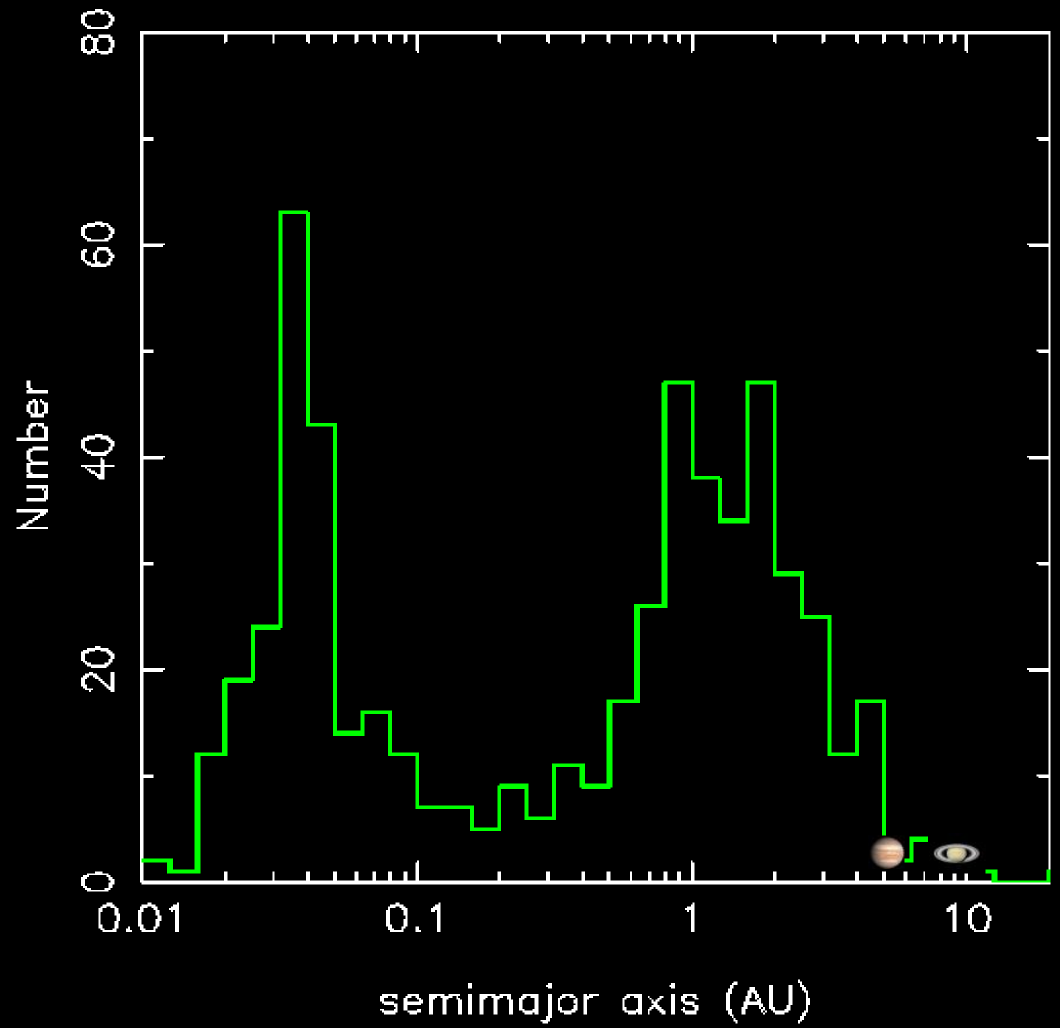


Thus, the SE migrates only as far as the giant planet does

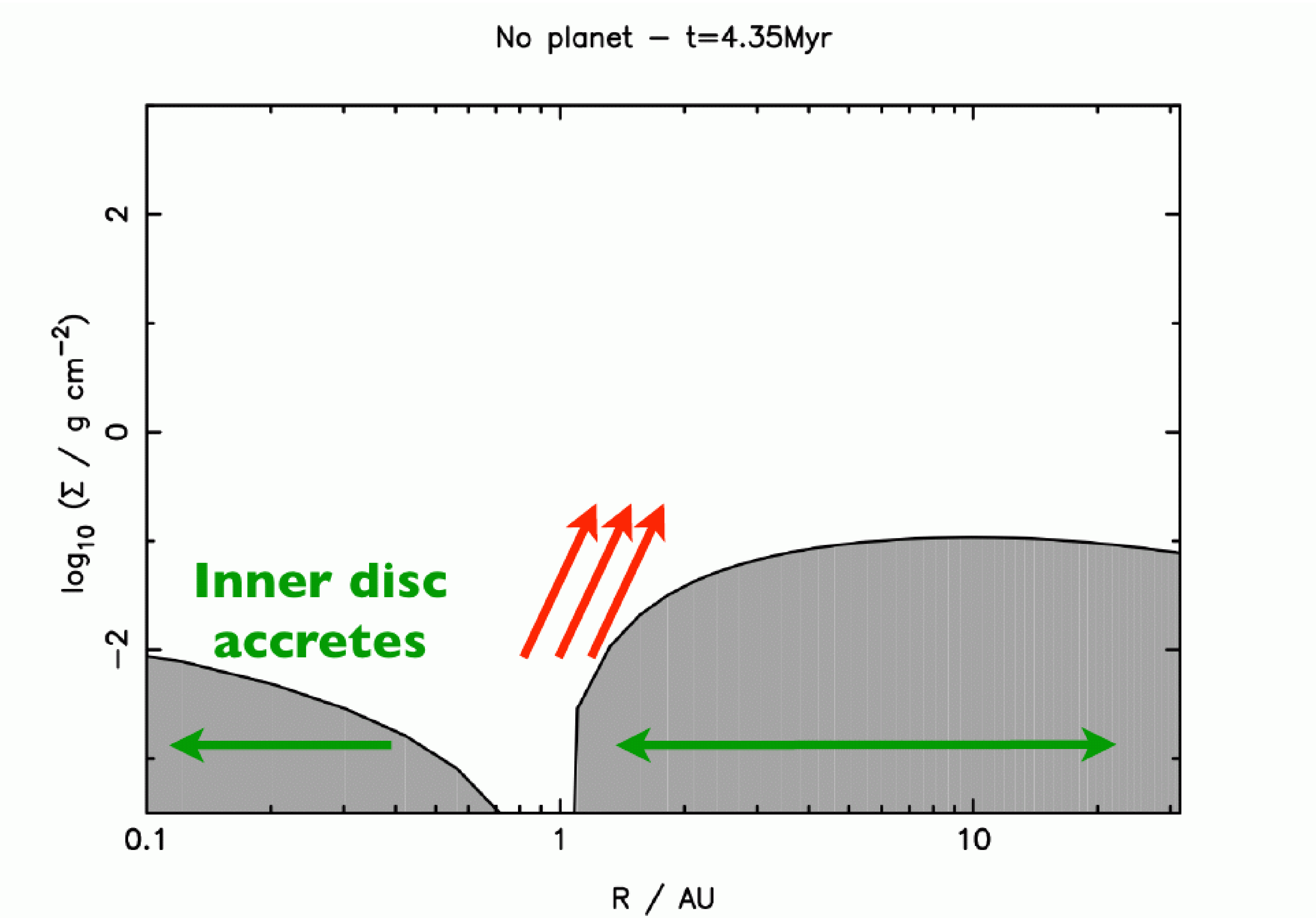
How far in can a giant planet migrate?

Indeed, most giant planets are located > 1 AU

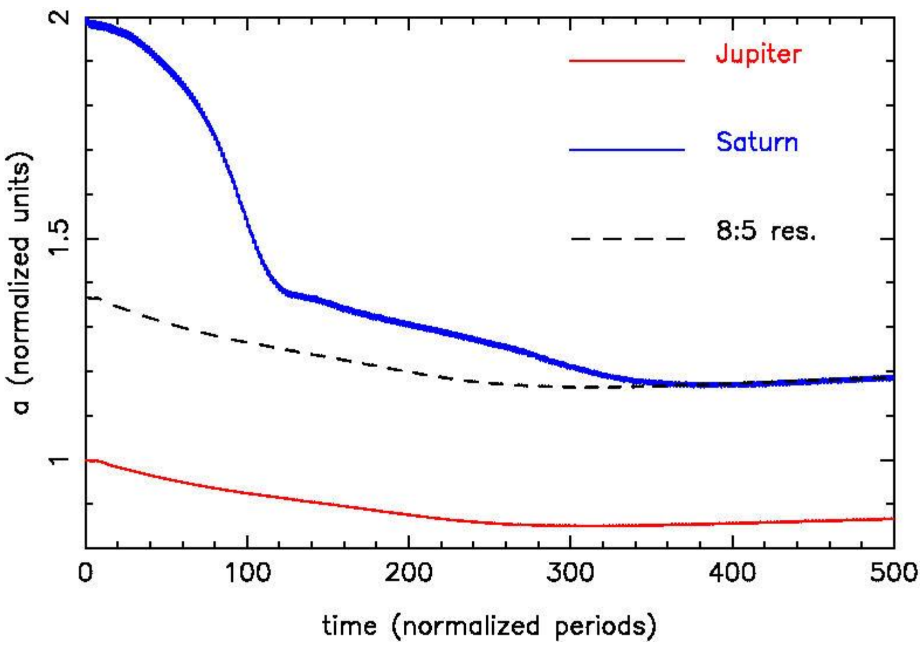
Observed radial distribution of giant planets (more massive than Saturn)



The explanation being that they don’t’ reach 1 AU before that photo-evaporation has dented the disk Alexander and Pascucci, 2012)

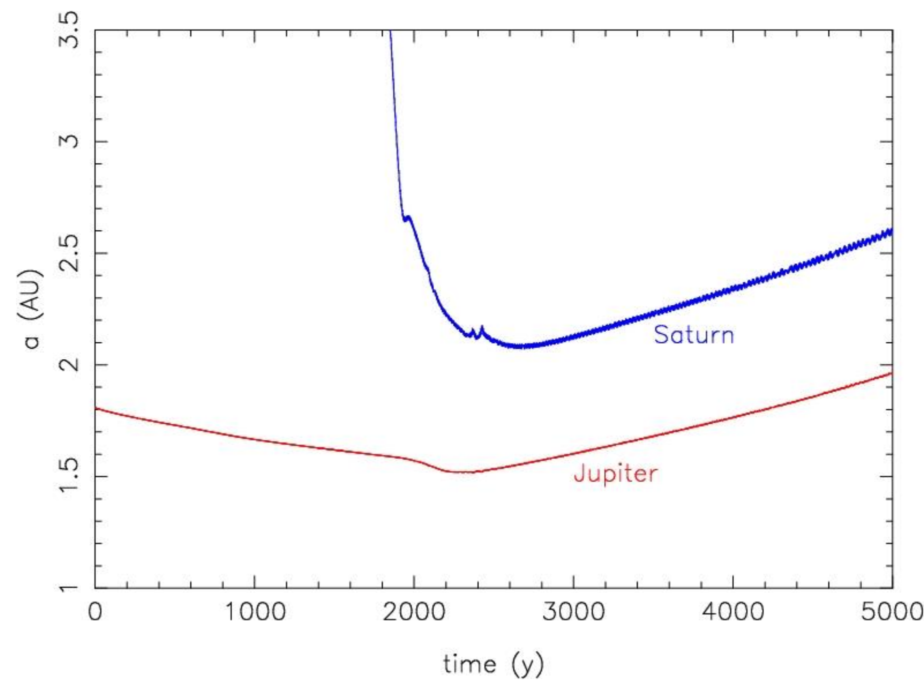


Type II migration isslowed down/reversed if there are 2 planets with a Jupiter/Saturn mass ratio



Masset and Snellgrove, 2001
(large H/r)

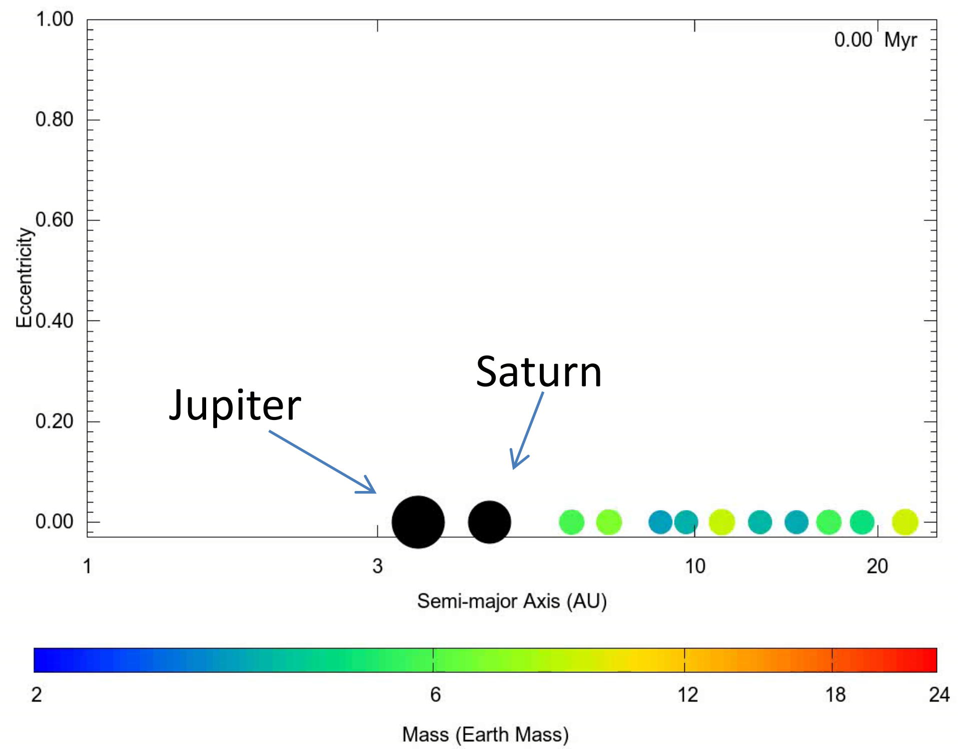
Morbidelli and Crida, 2007
(small H/r)



ORIGIN OF URANUS AND NEPTUNE

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 2015
Jakubik et al., 2012

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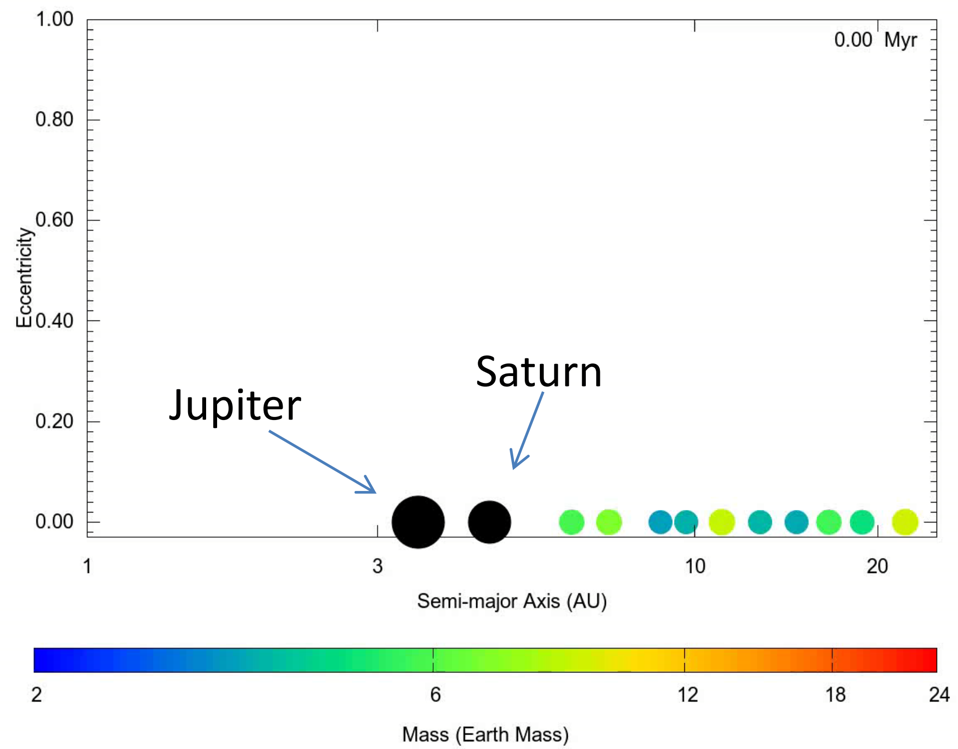
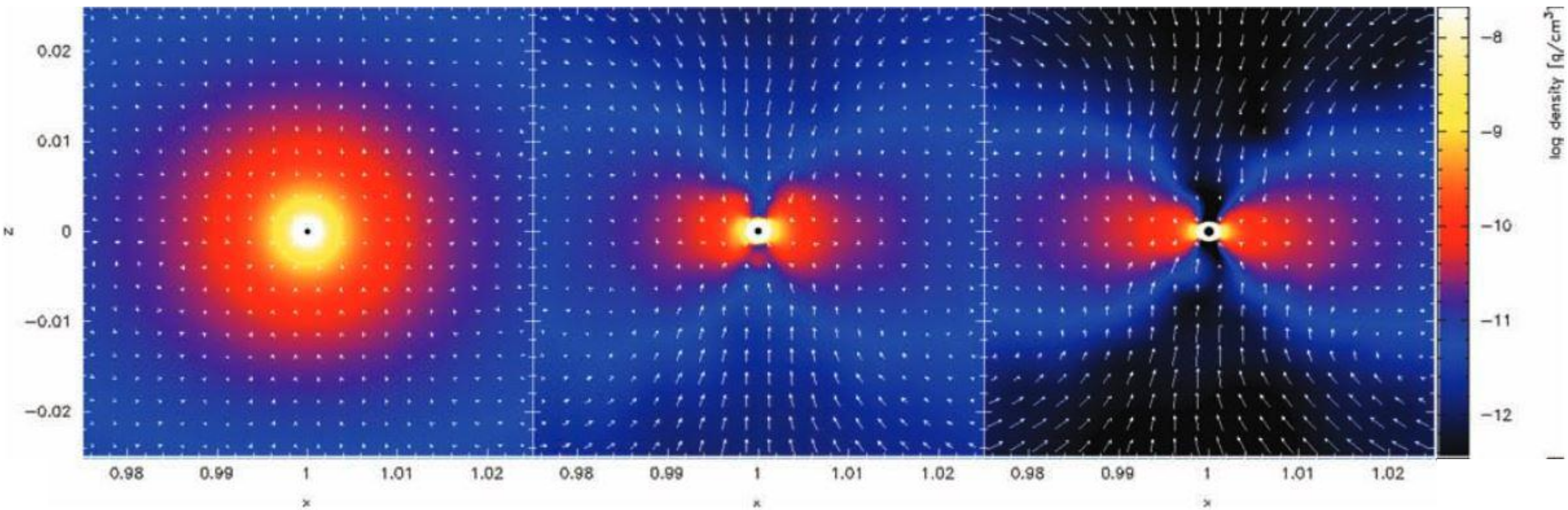


Izidoro et al., MNRAS 2015
Jakubik et al., 2012

In absence of Jupiter and Saturn, the embryos formed beyond them would have migrated into the inner Solar System forming a system of hot super-Earths

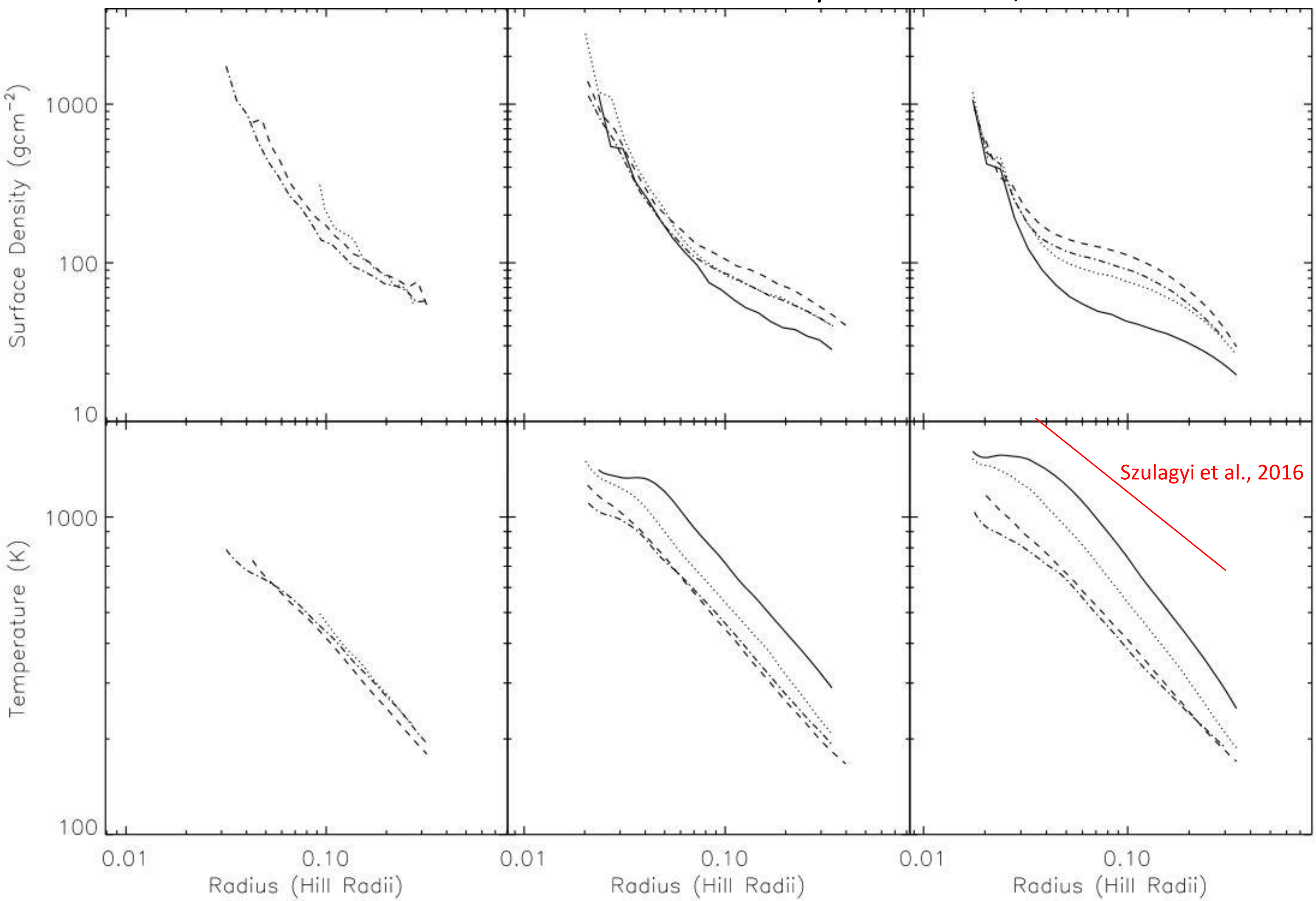
CIRCUM-PLANETARY DISKS

Ayliffe and Bate, 2009



100 M_E **166 M_E** **333 M_E**

Ayliffe and Bate, 2009



100 M_E **166 M_E** **333 M_E**

Hot temperatures in the CPD

Why are all satellites icy?

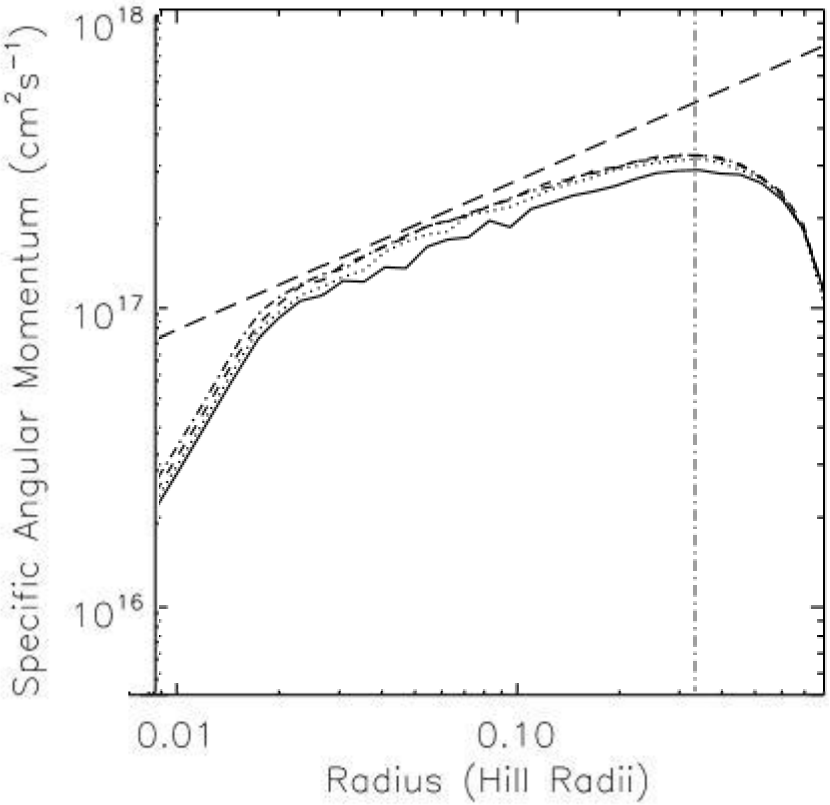
Disks can cool at a later stage, once the influx of gas from the circum-stellar disk becomes weak.
The fact that some satellites (Callisto, Titan) are not fully differentiated also argues for a late formation of satellites.

Why don't we see a first generation of rocky satellites?

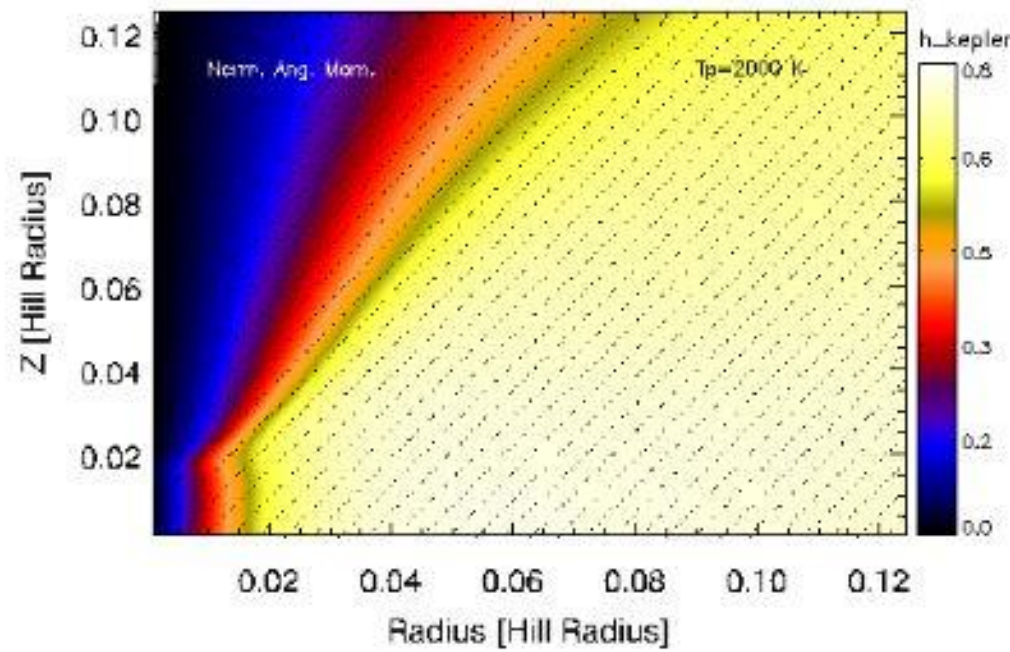
Did early satellites fell into the planet (Ward and Canup, 2010)?

Satellite formation by SI and PA has never been studied and could bring interesting results.
The CPD is very sub-keplerian.
The parameter η is ~0.2 whereas in the circum-stellar disk it is ~2.5×10^{-3}

Ayliffe and Bate, 2009

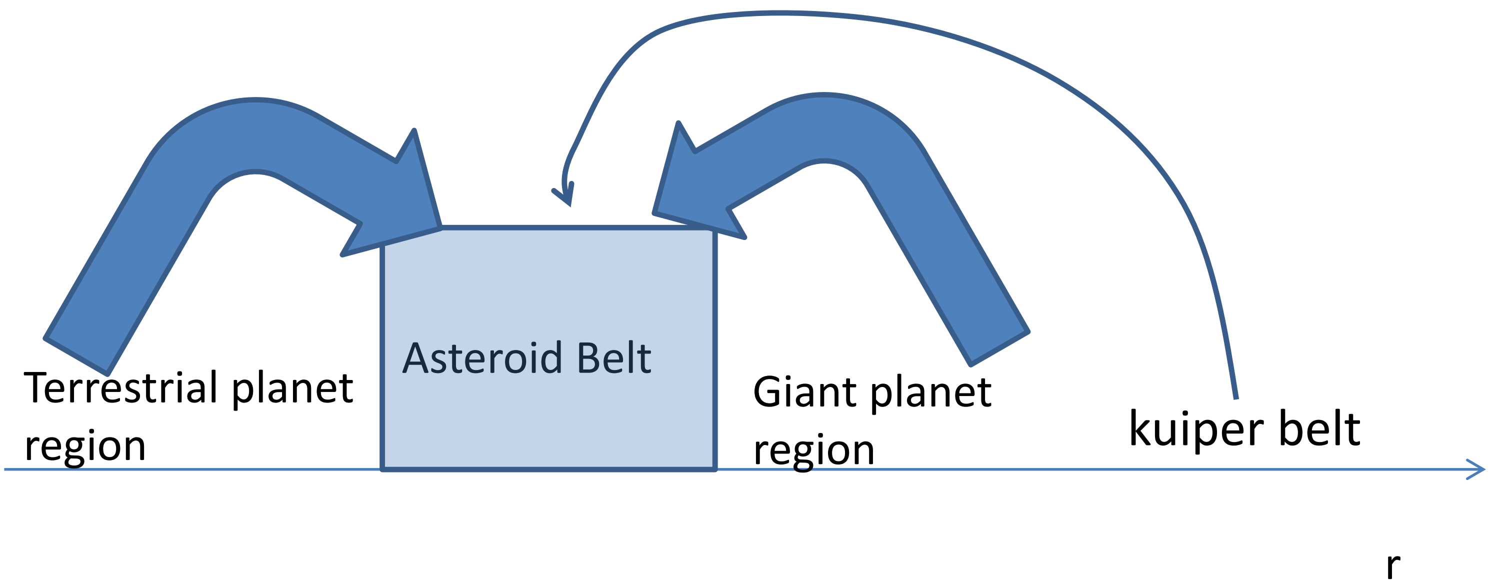


Szulagyi et al., 2016

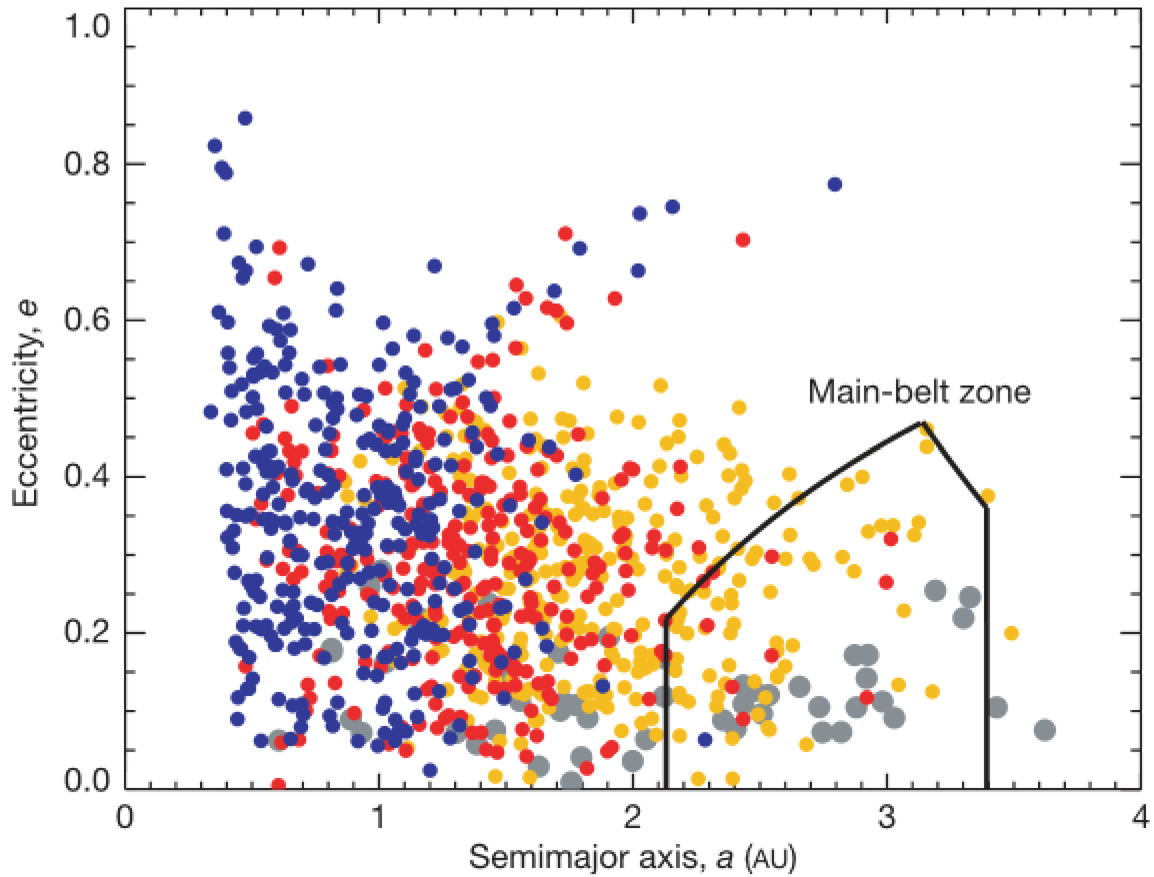


When the only solids available are small silicate grains, the large value of η may prevent the SI to occur -> no rocky satellites

Bonus: Radial dynamical mixing of planetesimals

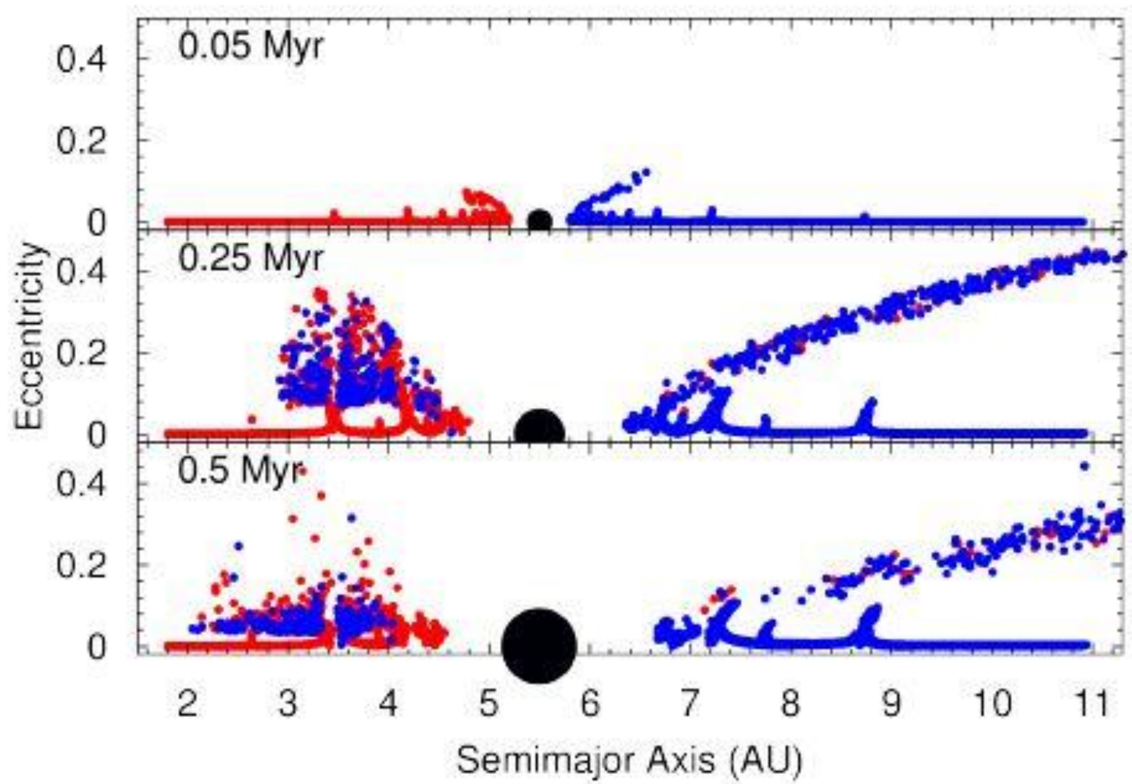


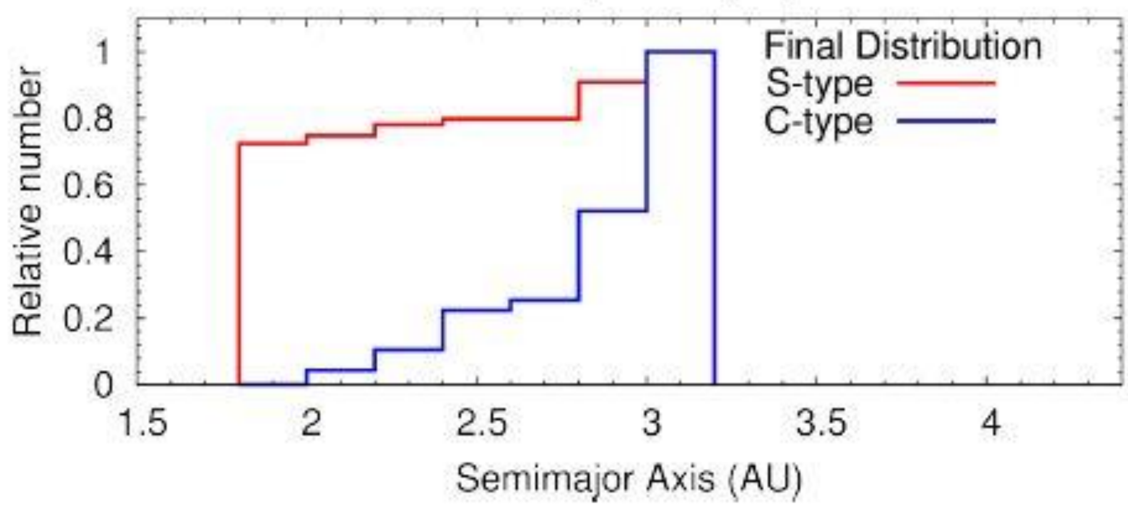
Bottke et al. (2006) showed that planetesimals can be implanted in the asteroid belt from the terrestrial planet region and proposed that the implanted bodies are the parent bodies of differentiated meteorites.



The implantation efficiency can vary from model to model, but the concept remains true

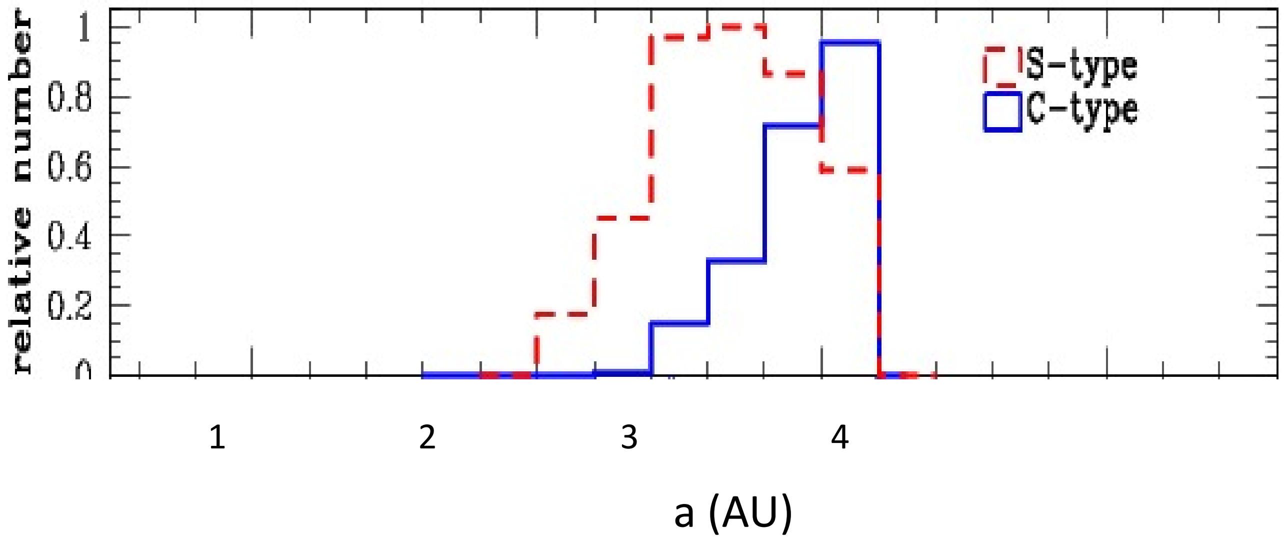
Bodies can be implanted into the asteroid belt from the giant planet region during the planet growth, via scattering and gas drag (Izidoro et al., 2016)

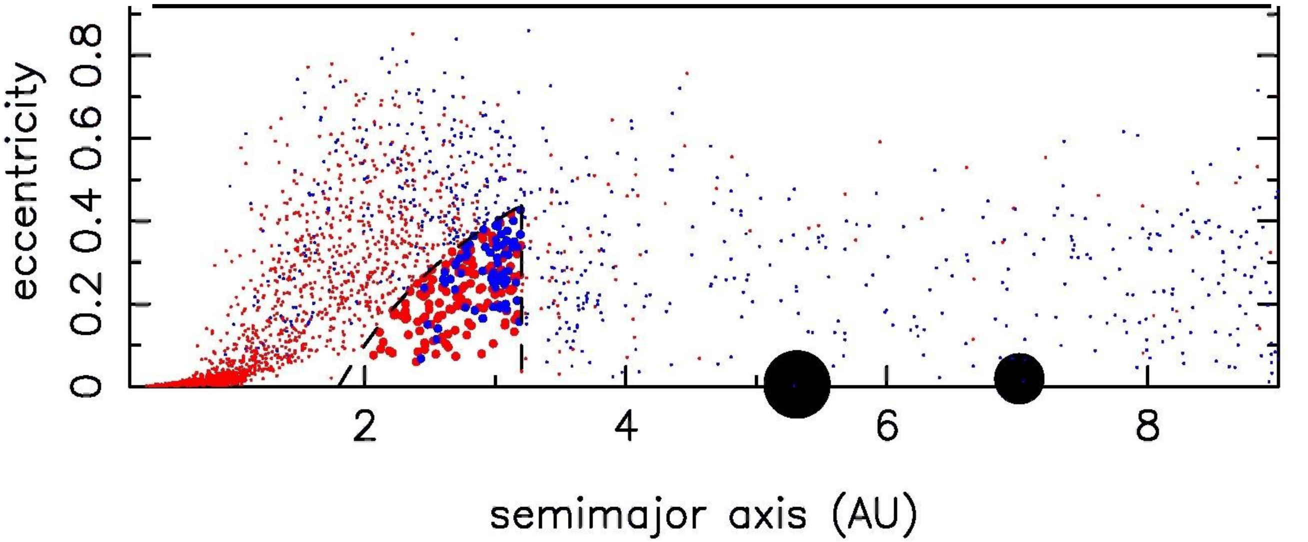




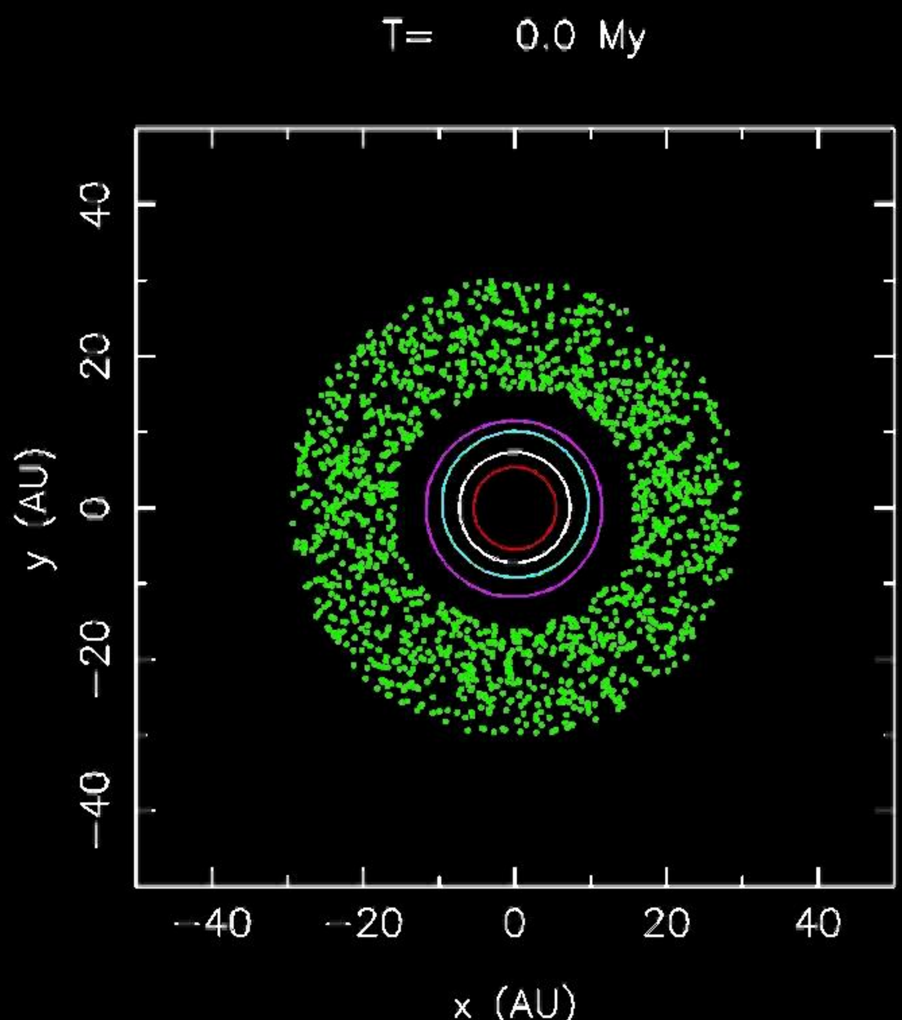
…or during Jupiter outward migration (Walsh et al., 2011)

Are they C-type asteroids?
Main belt comets?
Parent bodies of (some) carbonaceous chondrites?





Finally, trans-Neptunian objects can be captured in the asteroid belt during the giant planet instability that brought the giant planets onto their current orbits



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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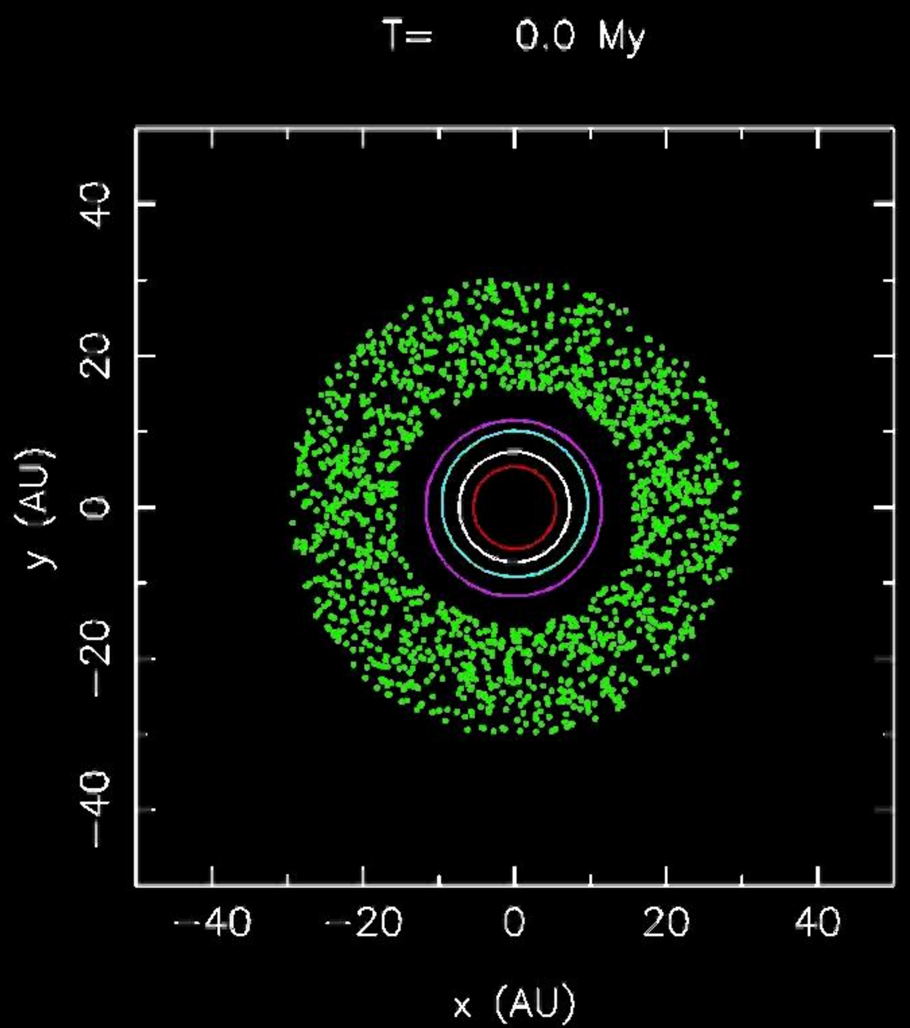
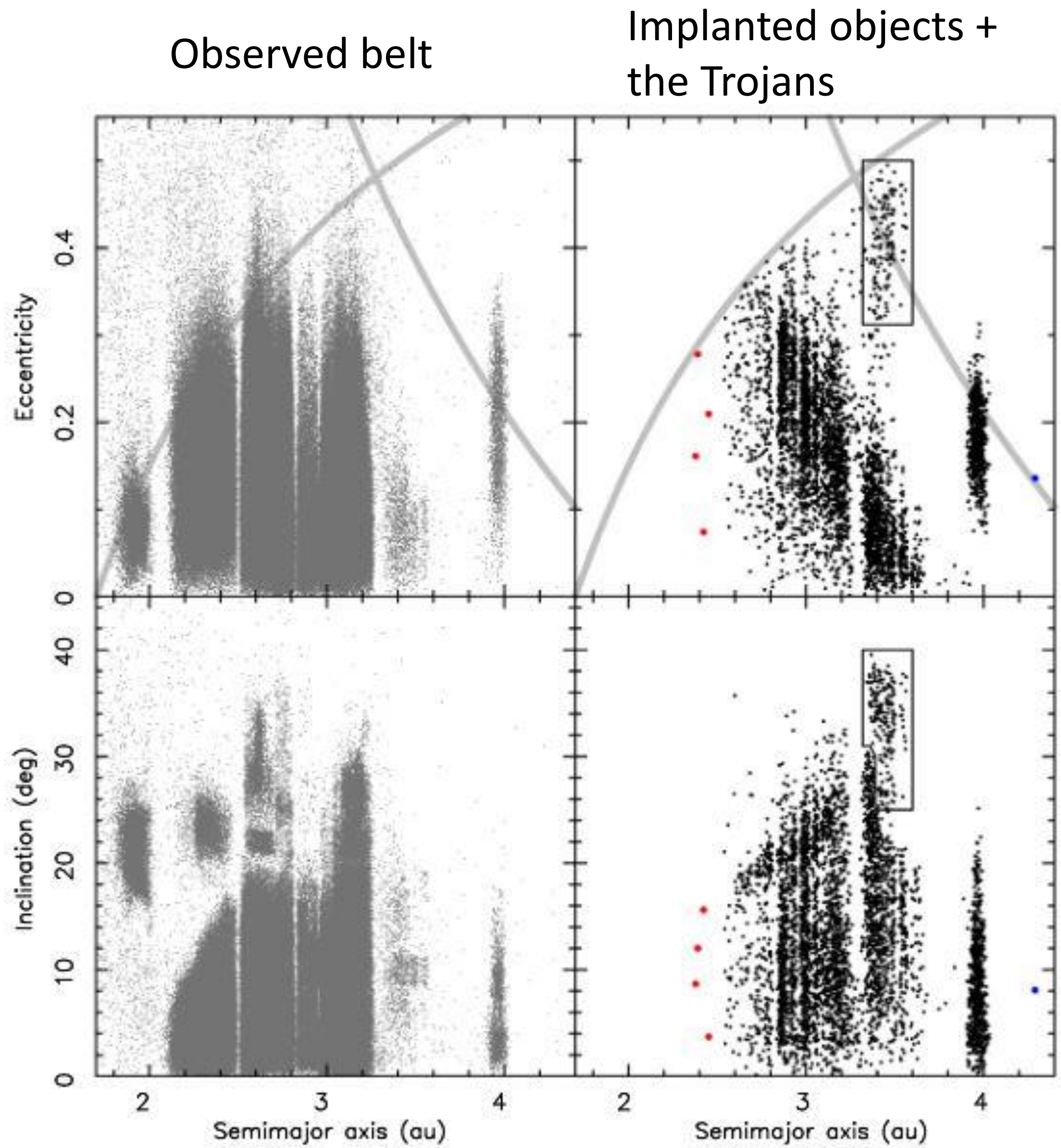


The Nice model:

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

Because Trojans are D-type, it is expected that trans-Neptunian objects implanted in the main belt are D-type too.



Levison et al., 2009; Vokrouhlicky et al., 2016

CONCLUSIONS

- **Our understanding of how planetesimals formed is still not consolidated**
- **The streaming Instability is a promising model**
- **It opens the possibility that planetesimals form early in some regions and at the end of the disk's lifetime in other regions**
- **Pebble accretion explains well the formation of the giant planets and the dichotomy of the Solar System**
- **Circum-planetary disks are extremely hot, so icy satellites could form only at very late stages**
- **Unveiling the internal structure of bodies is a powerful tool to deduce whether they formed early or late and therefore can help mapping accretion timescales as a function of location**
- **However, beware of radial mixing: not all bodies are born where they are.**