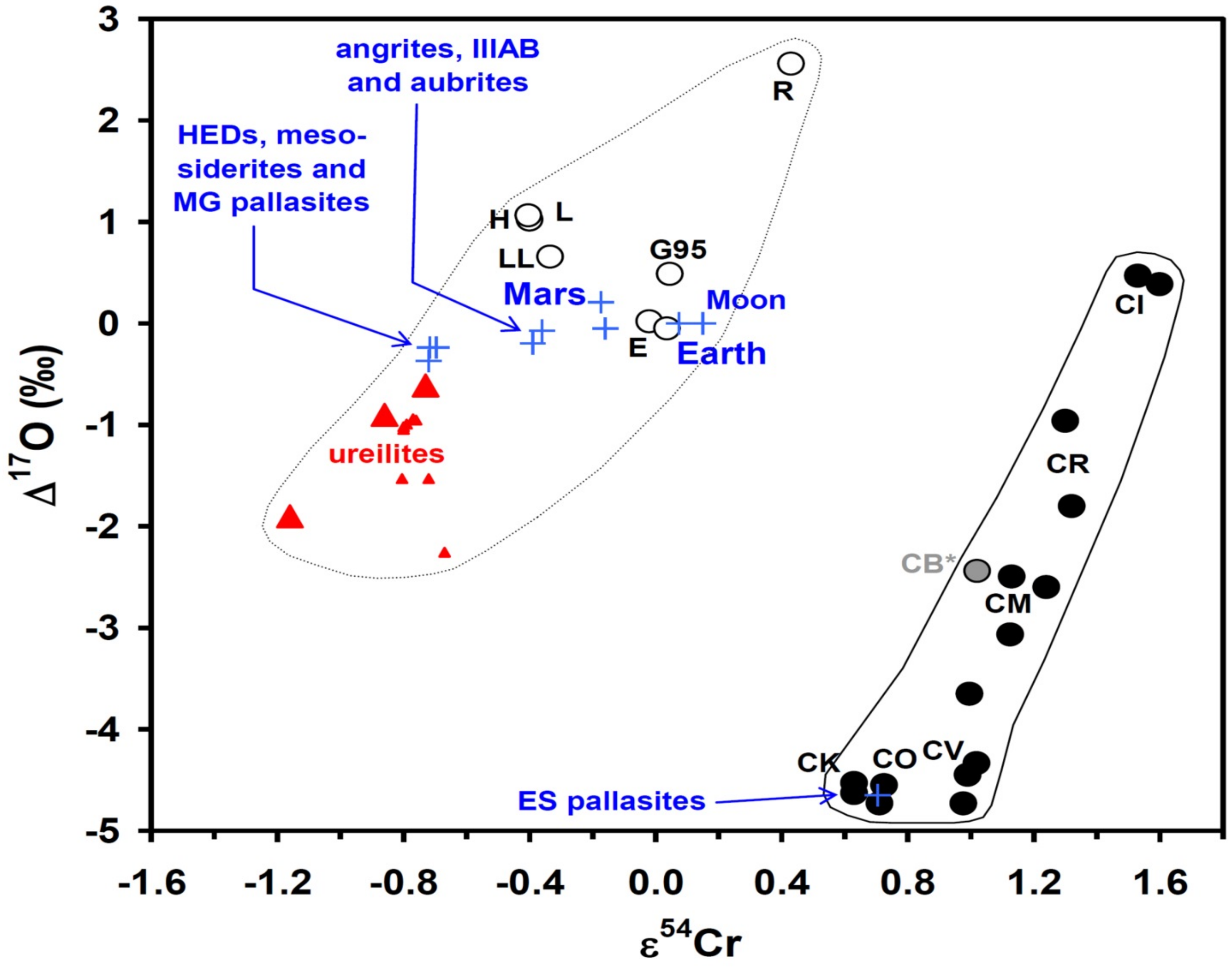
THE JUPITER BARRIER

A. Morbidelli – OCA - Nice

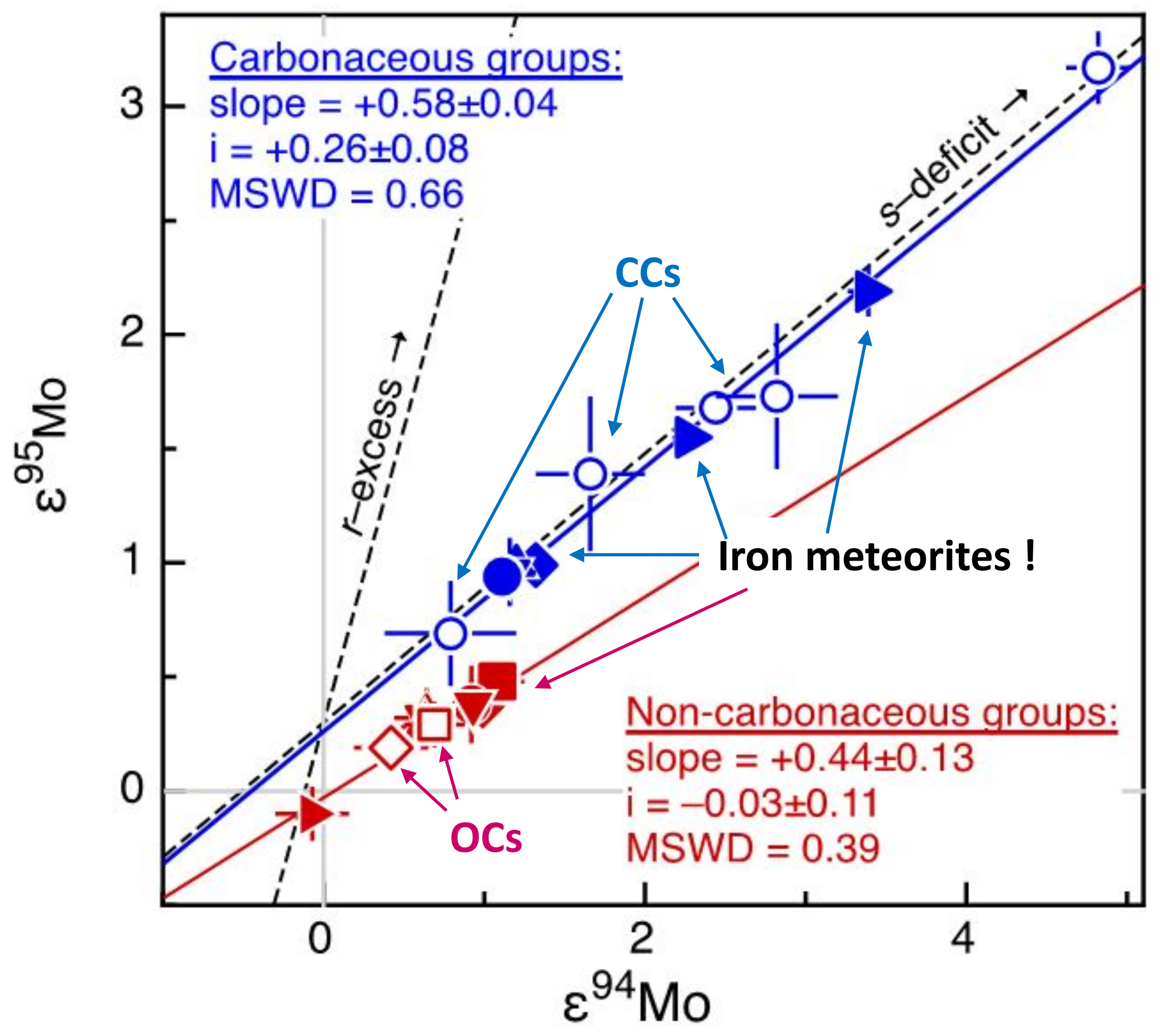
There are distinct isotopic reservoirs in the Solar System….



Modified from P. Warren (2011)

There are distinct isotopic reservoirs in the Solar System….

Separation in time or space?



Kruijer et al., 2017

Kruijer et al., 2017:

The two reservoirs were not separated in time.

Bodies with NCC isotopic composition

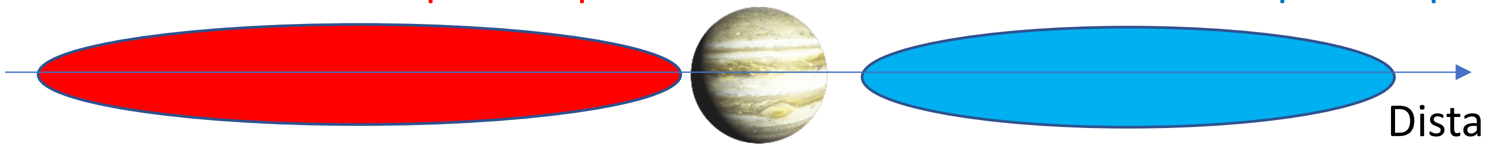
Bodies with CC isotopic composition

How could two reservoirs remain separate despite dust drift in the protoplanetary disk?

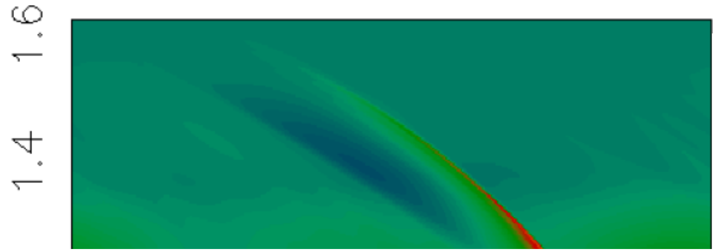
Hence they must have been separated in space, with a dynamical barrier precluding CC dust to reach the NCC reservoir

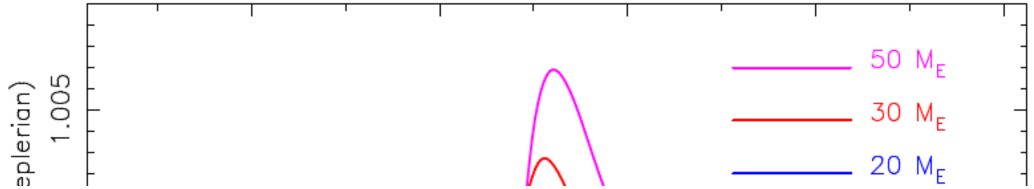
Bodies with NCC isotopic composition

Bodies with CC isotopic composition

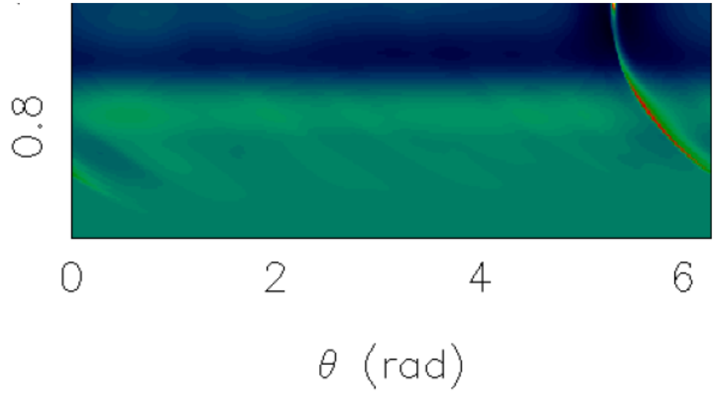


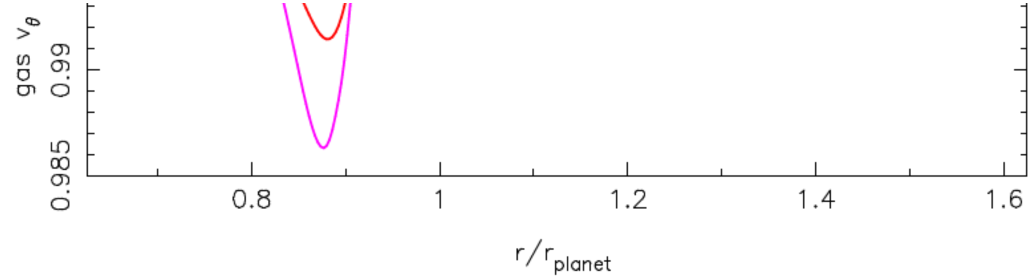
The concept of the Jupiter barrier





The real situation is more complex:
the effectiveness of the barrier depends on dust's size and other disk parameters





Lambrechts, Johansen and Morbidelli, 2014;
Morbidelli and Nesvorny, 2012

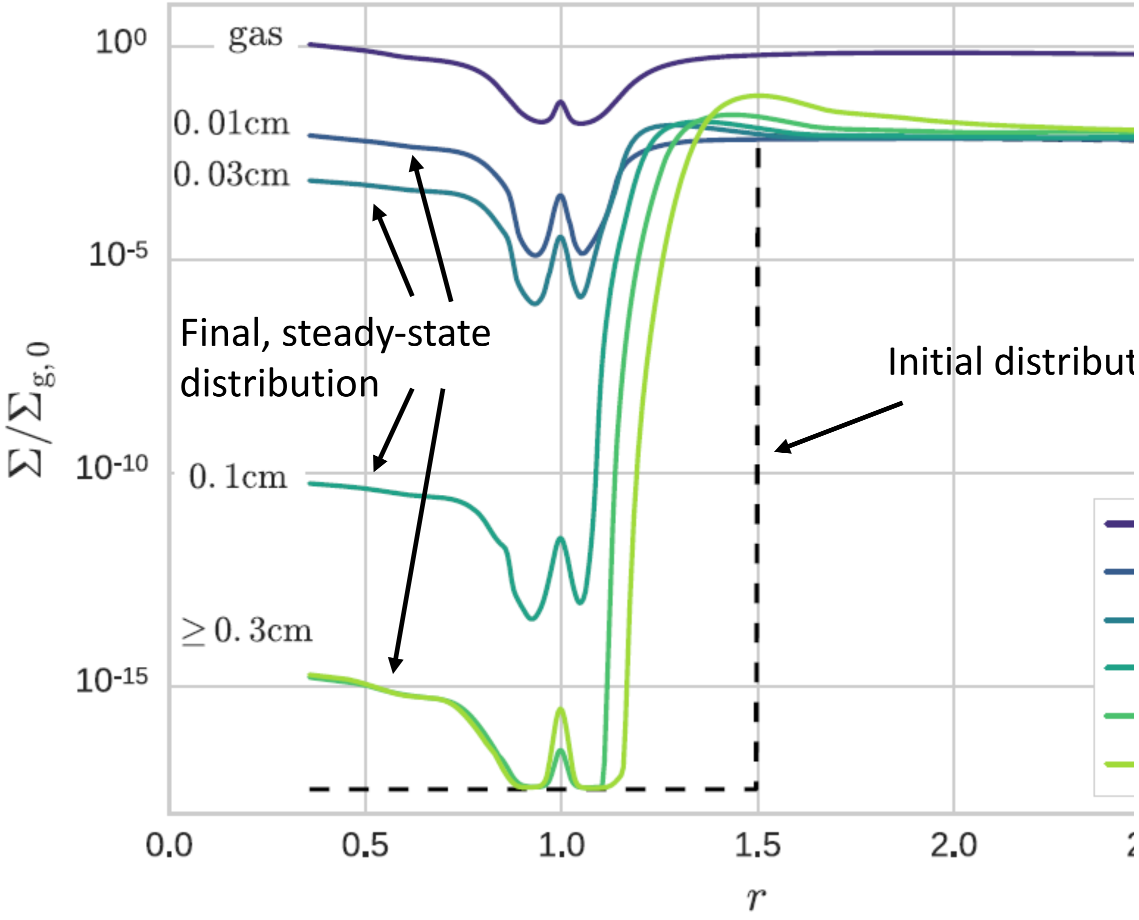
When a protoplanet reaches a mass of ~ 20 Earth masses, it produces a ring in super-Keplerian rotation, which should cut off the flow of condensed particles towards the inner disk

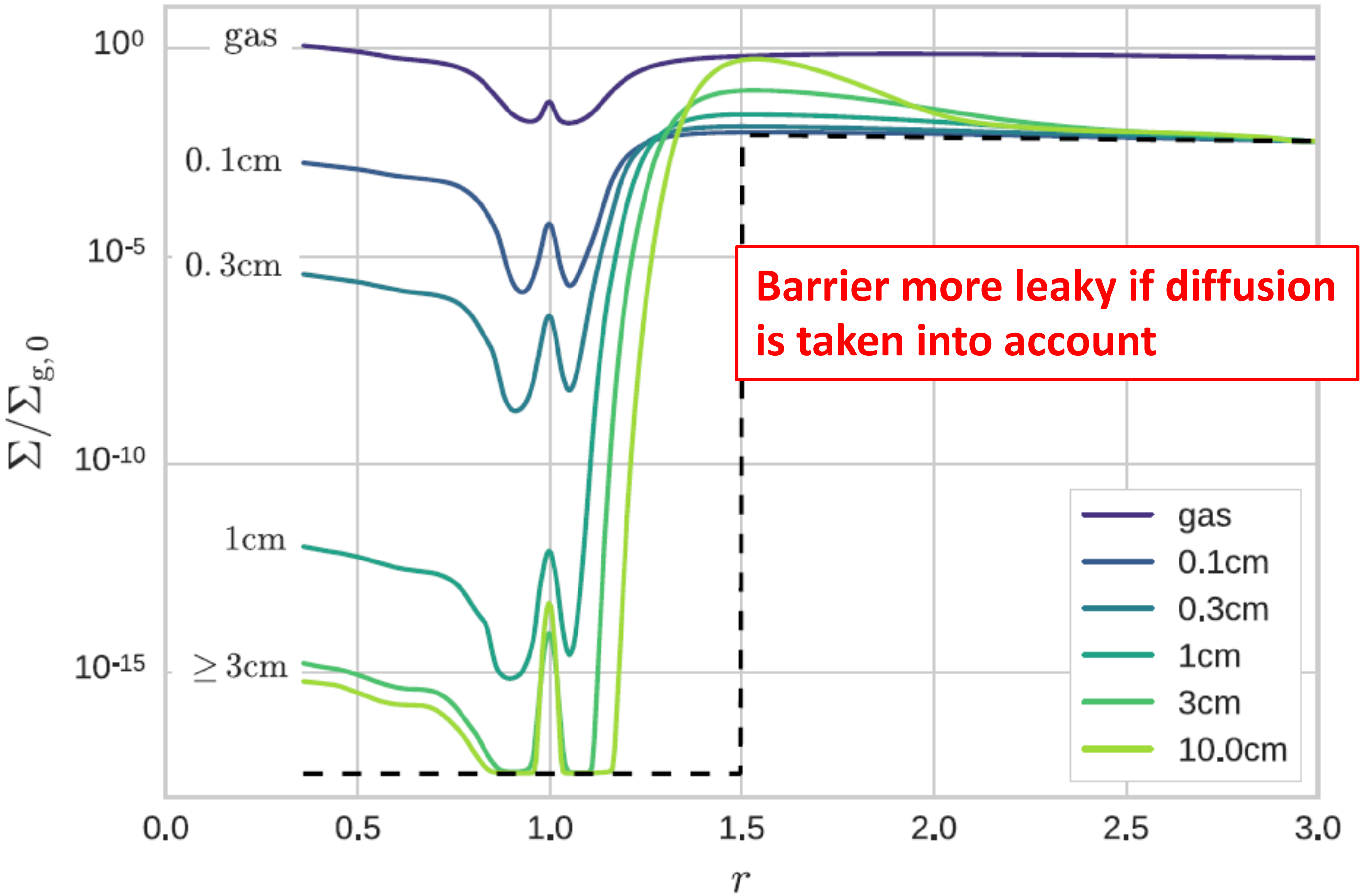
Kruijer et al: As CC iron meteorites formed at ~1My, Jupiter should have reached 20 Earth masses within this time

Most complete study of the Jupiter's barrier in P. Weber Ph.D. project (Weber et al., 2018, ApJ, 854:150; Haugbolle, Weber et al., 2019, ApJ, 158:55):

hydrodynamical simulations of gas AND dust, using FARGO3D (Benitez-Llambay & Masset 2016, Benitez-Llambay et al. 2019)

Weber et al. 2018: Jupiter-mass planet, $\alpha=3\times10^{-3}$

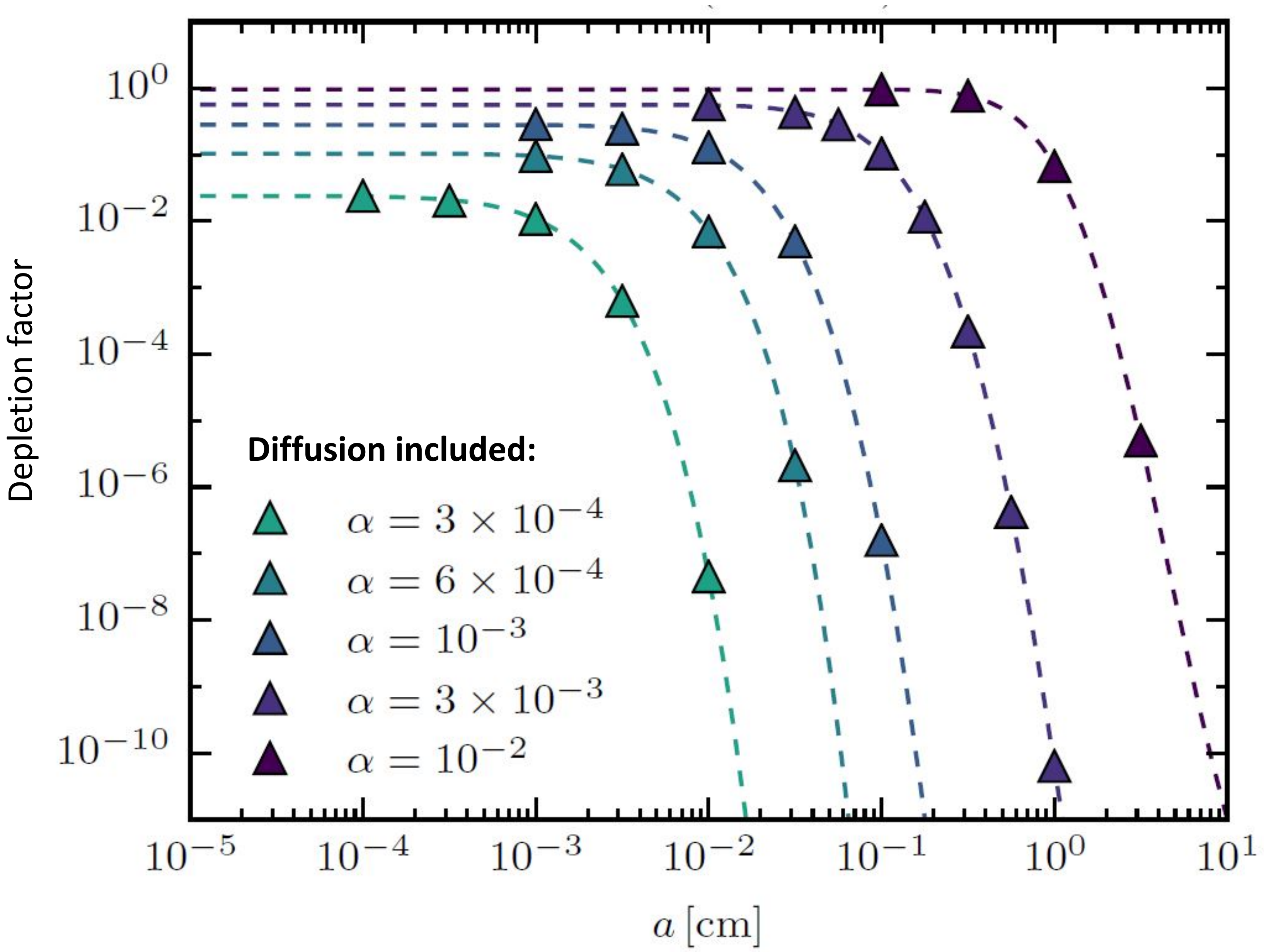




Strong dependence on disk's viscosity

Haugbolle et al., 2019 :
Jupiter-mass planet

The difference between the diffusion and the diffusion-less cases becomes smaller with decreasing α

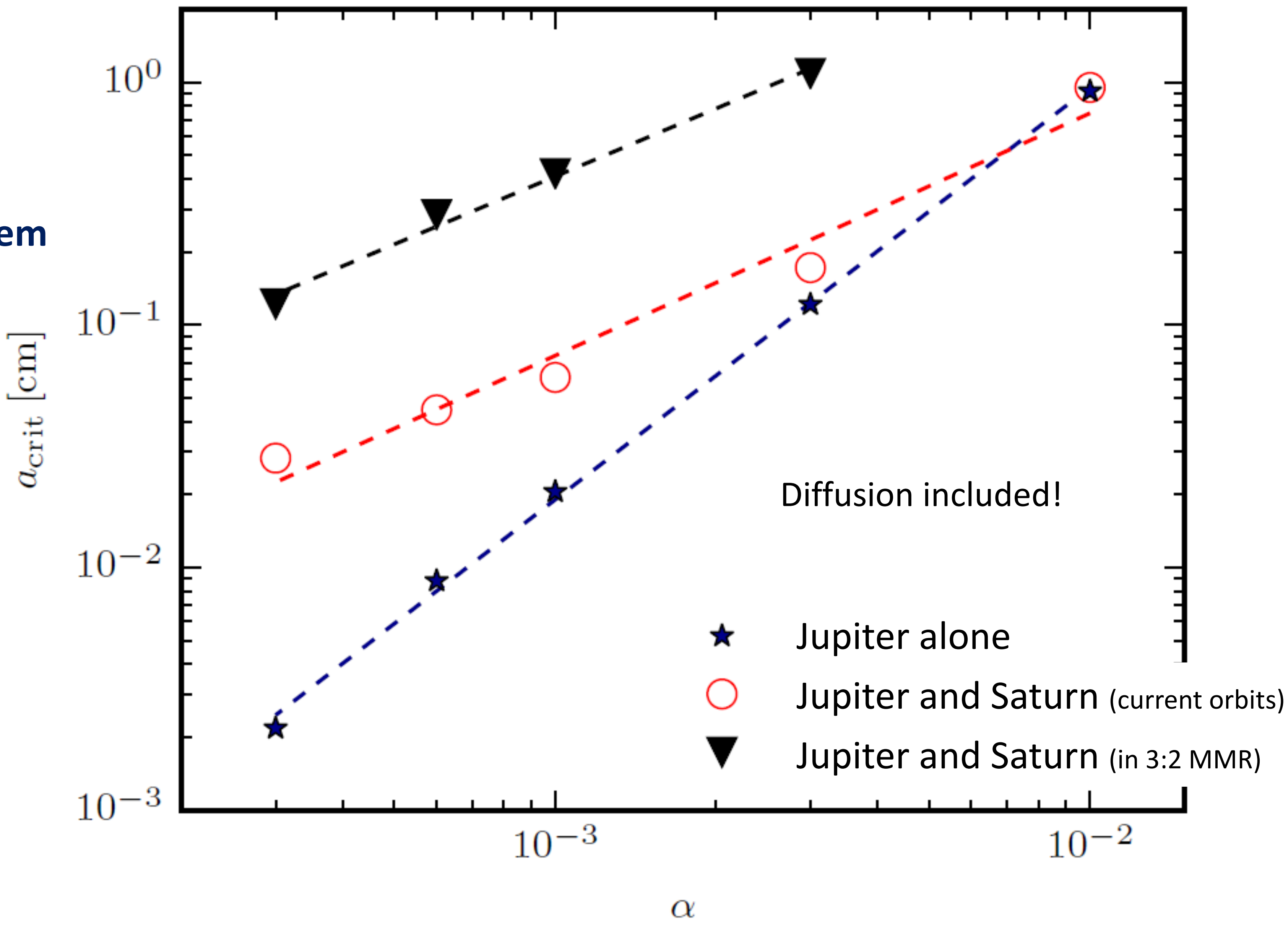


Jupiter is not alone: this also makes the barrier more leaky

Size of particles for which there is a 90% depletion in the inner solar system

NOTE: effects of planet migration not modeled yet

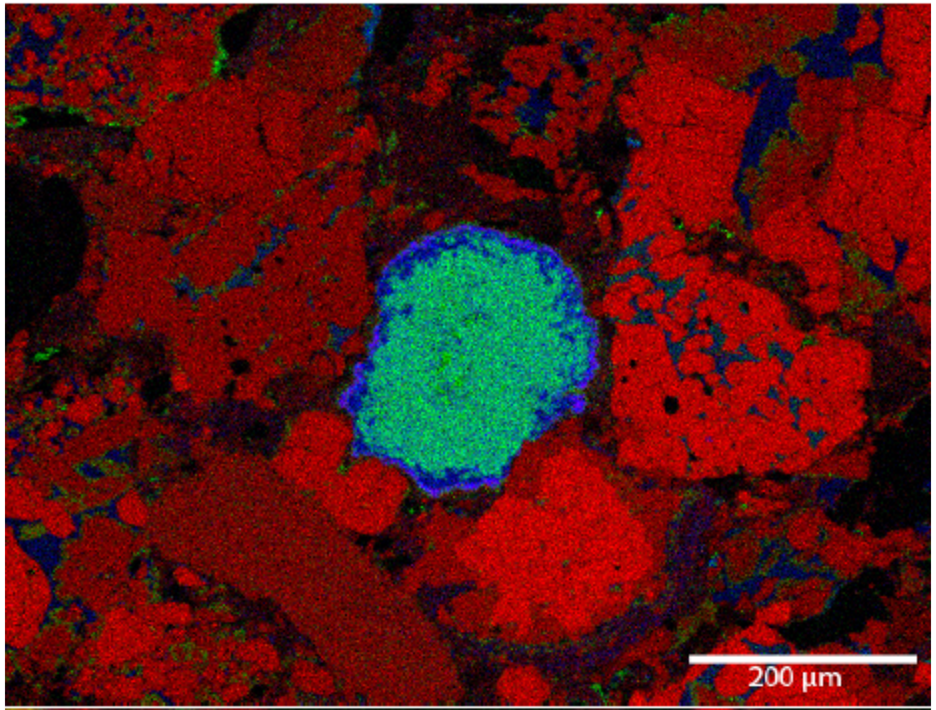
Haugbolle et al., 2019

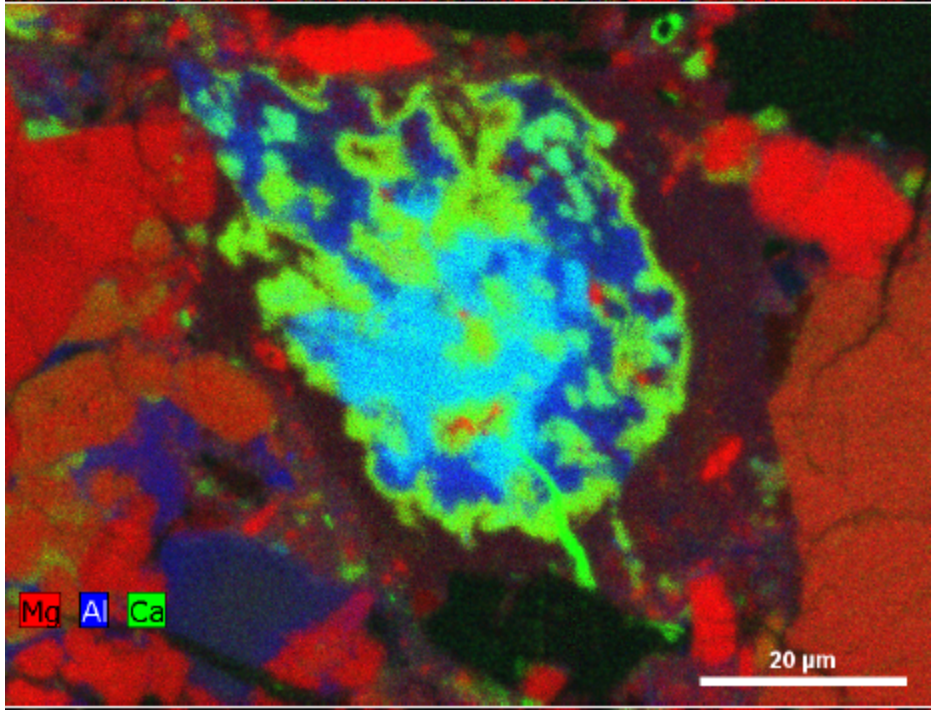


Which particle sizes were affected by the barrier?

- Haugbolle et al., 2019 searched for CAIs in OCs.
- They did not find any > 200µm.
- The fractional area of CAIs > 100µm in OC is 10^{-5}, compared to a fractional area of 4-10% in CCs.

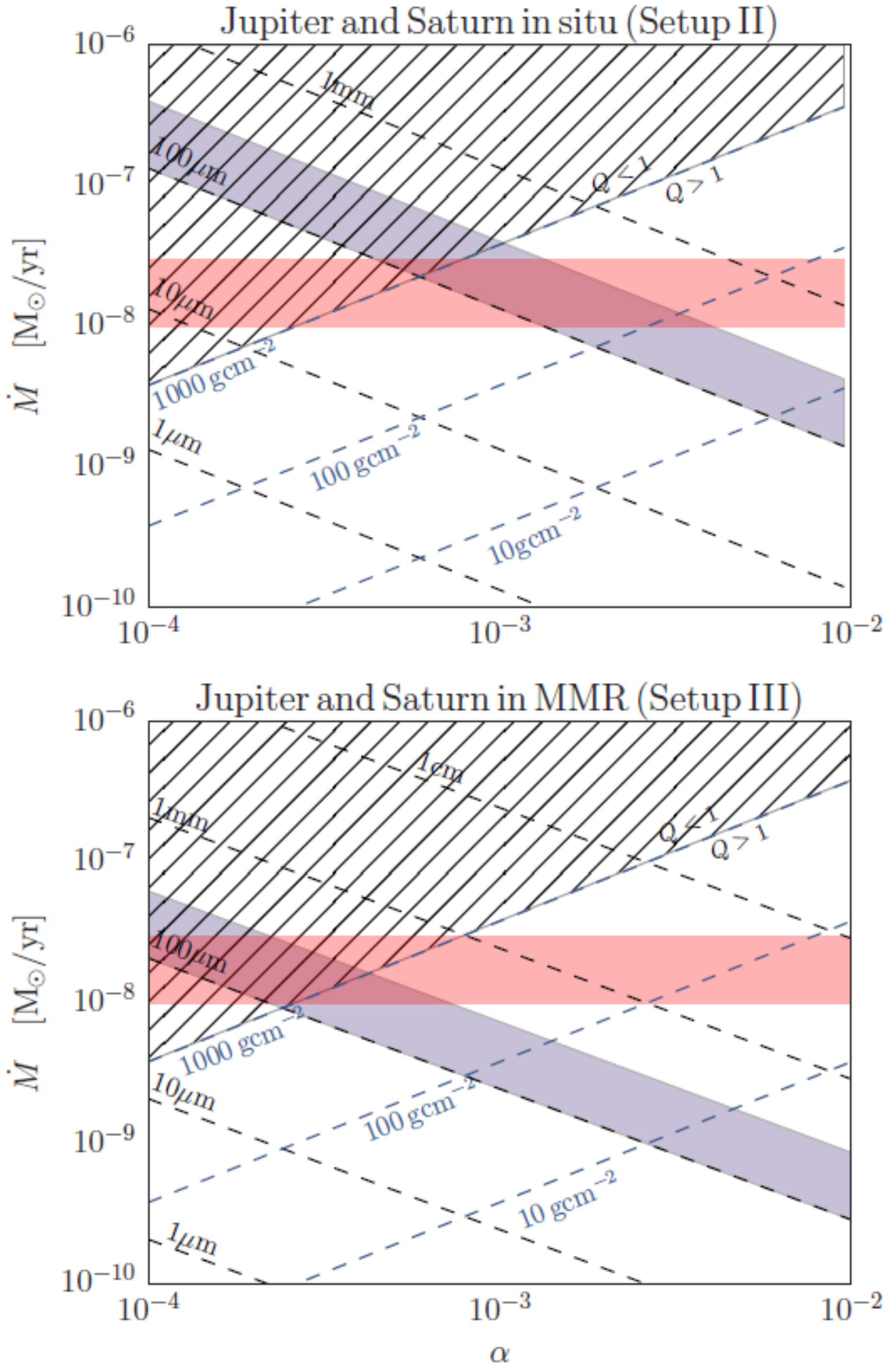
THE BARRIER WAS EFFECTIVE ALREADY AT 100µm





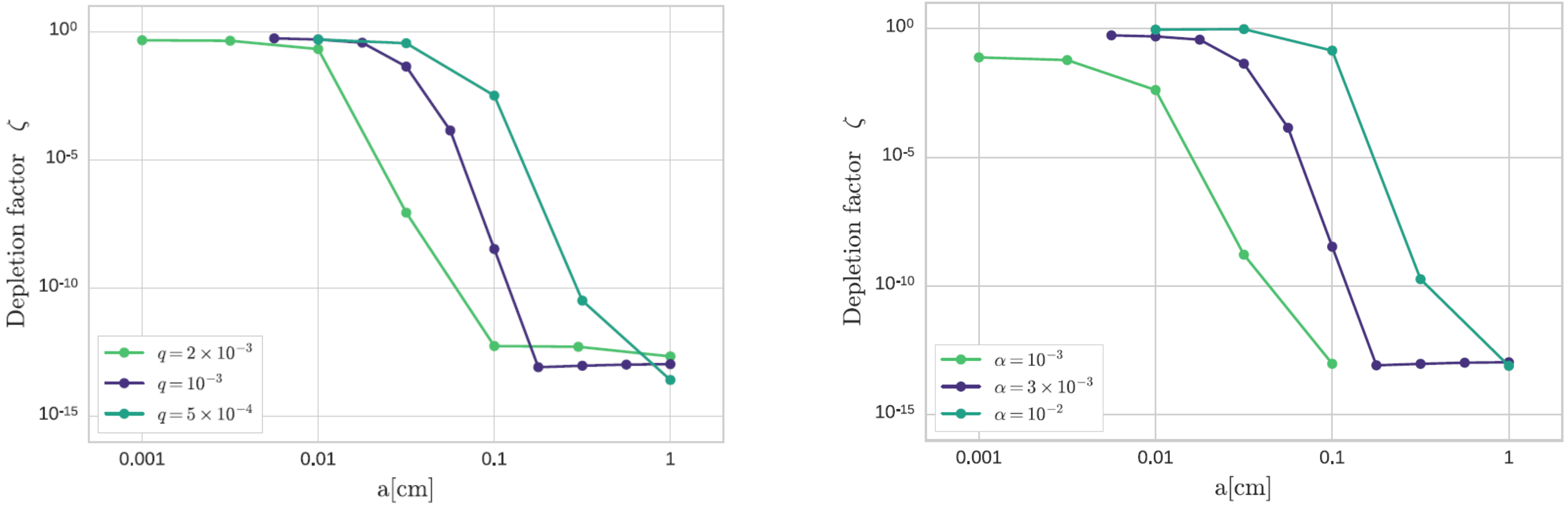
Haugbolle et al., 2019:
The disk must have been such that the flux of 100-300μm particles was cut-off by at least when Jupiter and Saturn reached final masses

Suggests strongly that the disk had a small viscosity: $\alpha < 10^{-3}$



$\alpha=10^{-3}$ is an upper bound because it's unlikely that Jupiter was $1M_J$ at t=1My

Weber et al., 2018: rough trade-off between planet mass and viscosity.
Similar effects from a planet 2x smaller in a 2x less viscous disk



Consistent with gap opening criterion: $\frac{3}{4}\frac{H}{R_{\rm H}} + \frac{50}{q\mathcal{R}} \lesssim 1$ with $\mathcal{R} = r_p^2 \Omega_p / \nu$ (Crida et al., 2006).

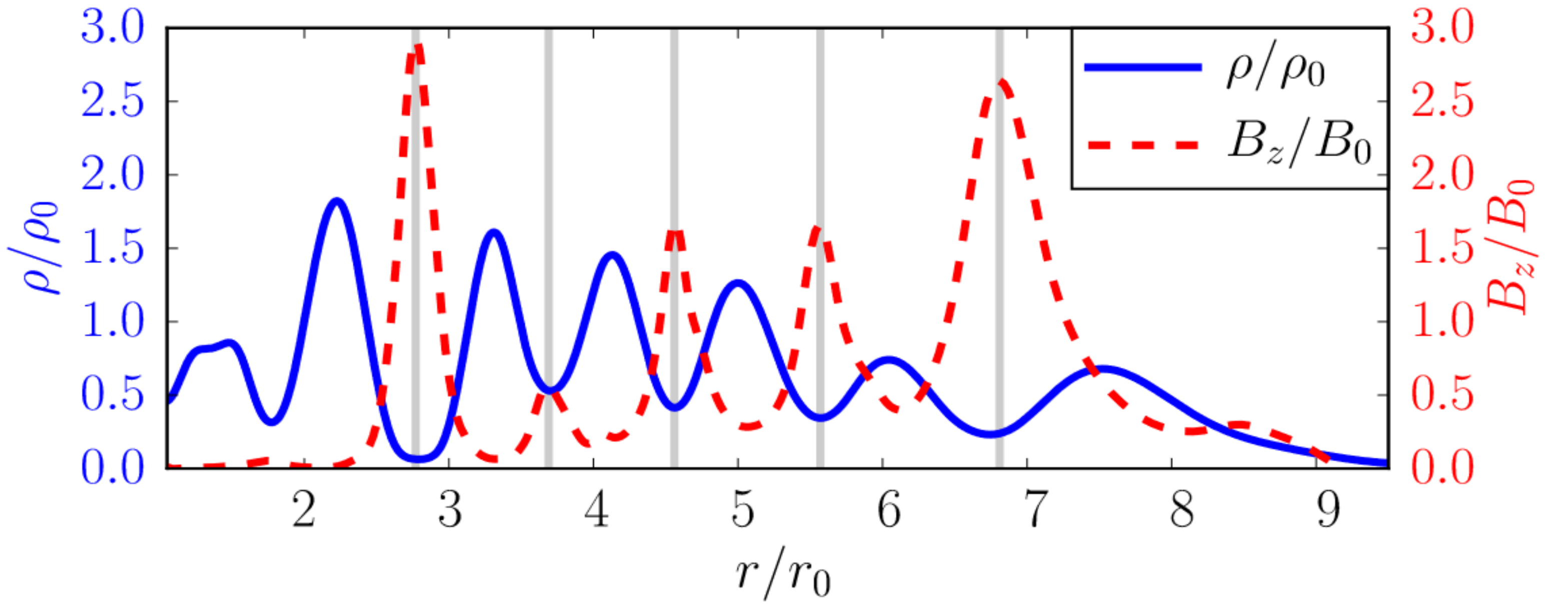
Supposing $\alpha \approx 10^{-4}$, this suggest that the 100-300µm barrier could have started with (proto)Jupiter at 30-50M_E

The Jupiter's barrier started at 30-50 Earth masses rather than 20

Growing to 30-50 M_E in <1 My is a formidable accretion performance

Perharps the barrier started as a pressure bump at the inner edge of a zonal flow and then Jupiter took over

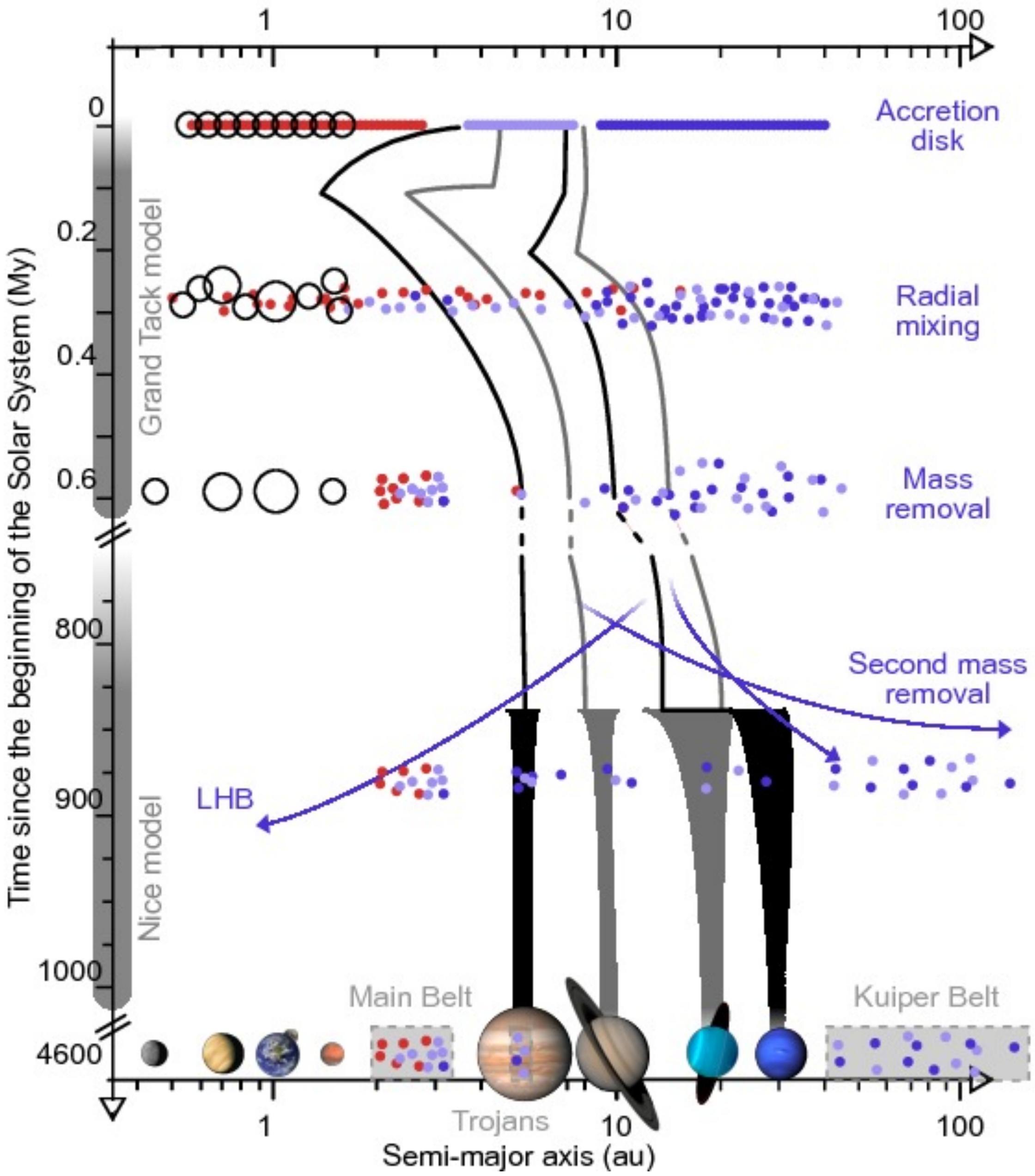
This could have been no coincidence: the zonal flow could have favored the formation of Jupiter



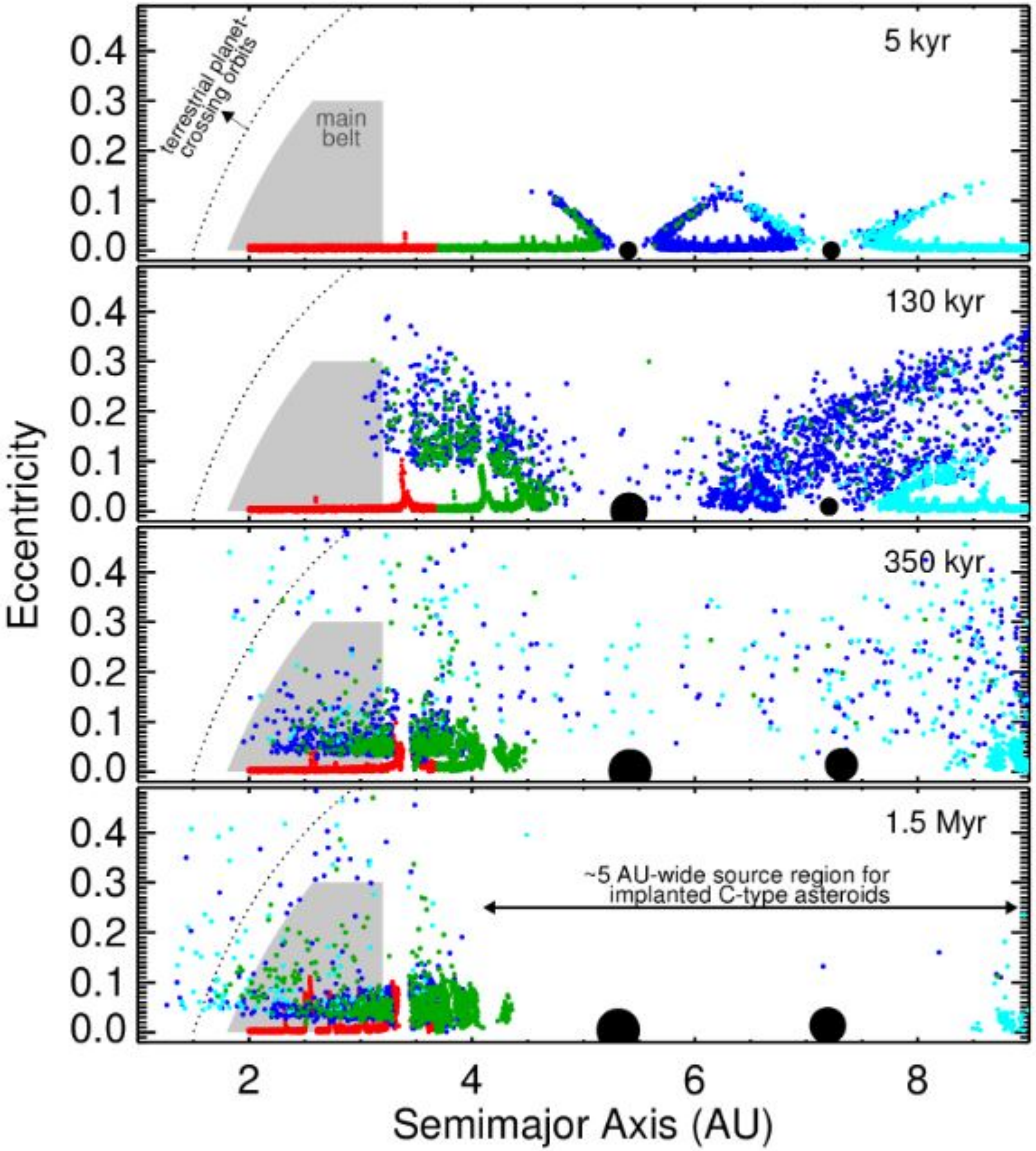
Béthune et al., 2017; see also Suriano's talk

If carbonaceous chondrites formed beyond Jupiter why are they in the asteroid belt today?

First possibility:
Jupiter's outward migration (Grand Tack) [Walsh et al., 2011]
Giant planet instability [Levison et al., 2009]



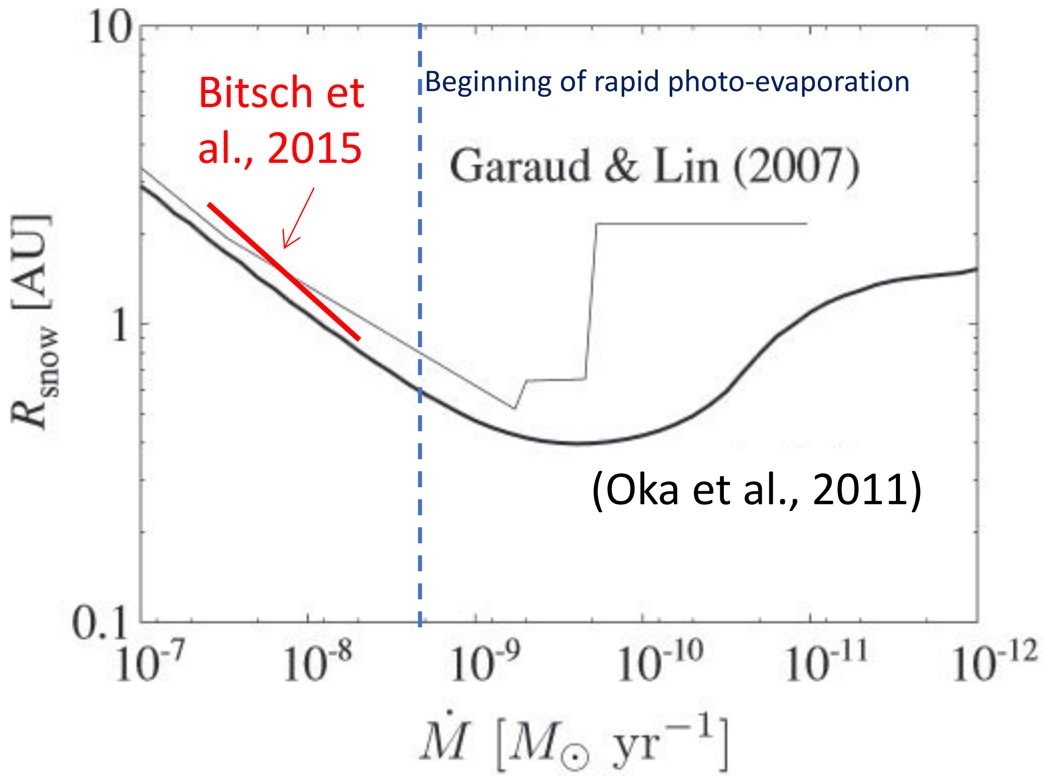
Second (more general) possibility:
Jupiter's growth + gas drag
[Raymond and Izidoro, 2017]



Raymond and Izidoro, 2017

Other, more substantial effects of the Jupiter barrier on the inner Solar System

i) The Jupiter barrier can also explain why the inner solar system is dry (Morbidelli et al., 2016)



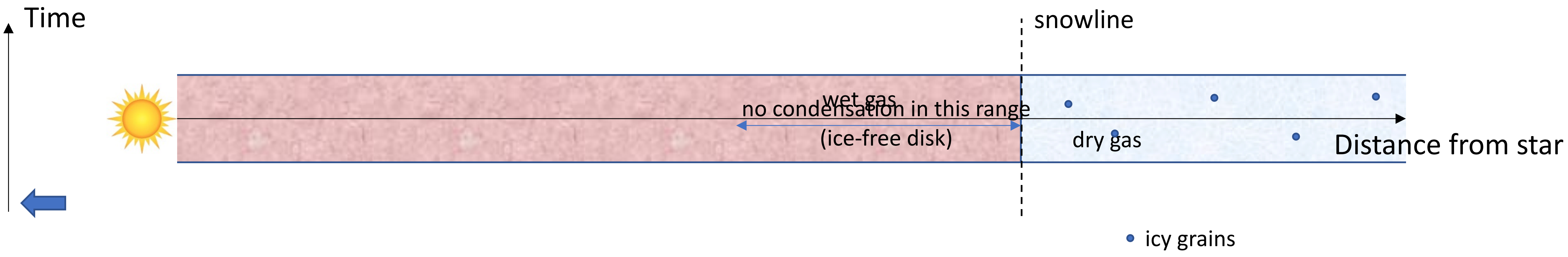
Protoplanetary disks should become cold as they evolve

Before they disappear, the snowline should be inside of 1 AU.

The Earth and all asteroids should be water-rich bodies
The composition of Solar System bodies suggests that the snowline fossilized at ~3AU

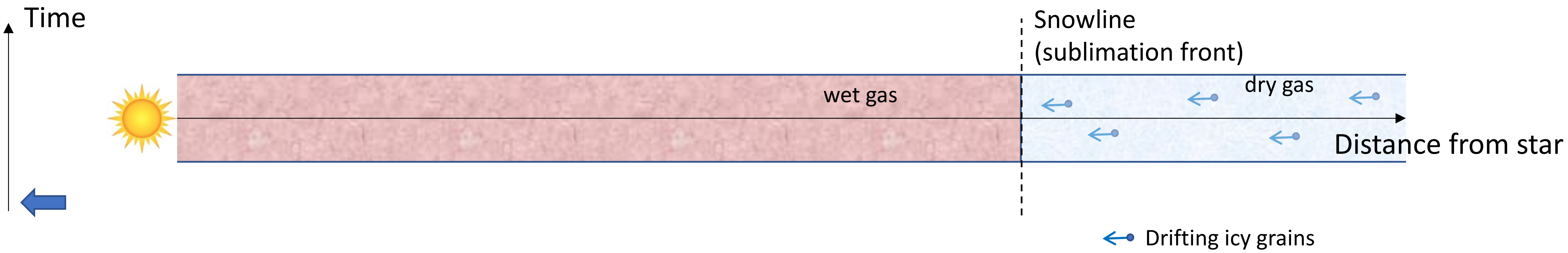
Even if the disk cools, there is no direct condensation of gas (after one viscous timescale)

I) An idealized case without icy grain radial-drift

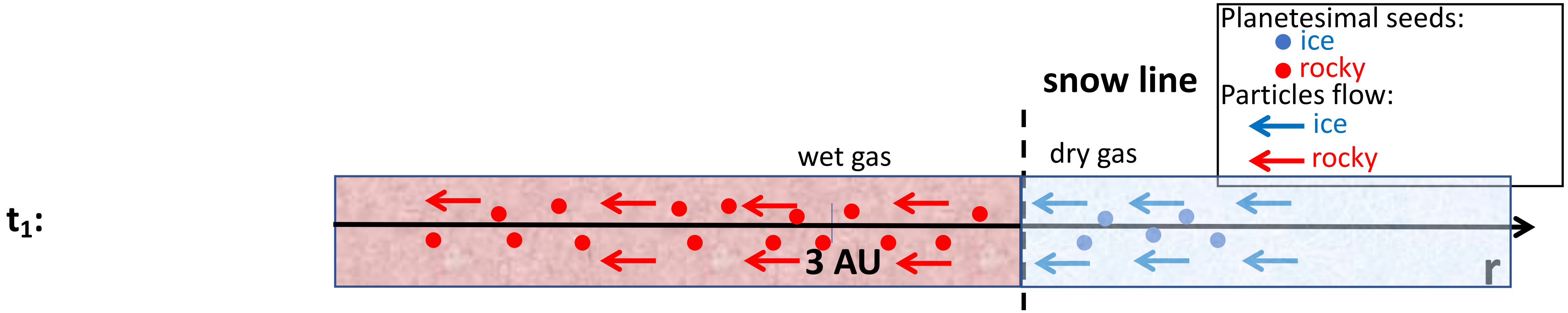


The reason for which a disk becomes icy beyond the snowline is the radial drift of icy-grains

II) A realistic case with icy grain radial-drift



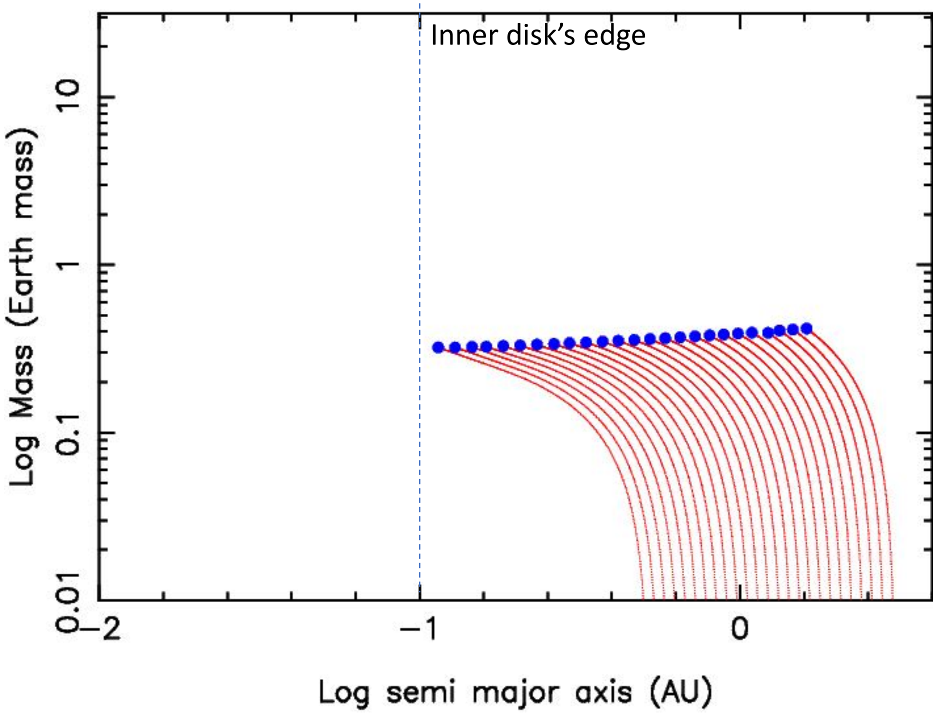
Keeping the inner Solar System dry despite disk-cooling requires to regulate the migration of icy grains



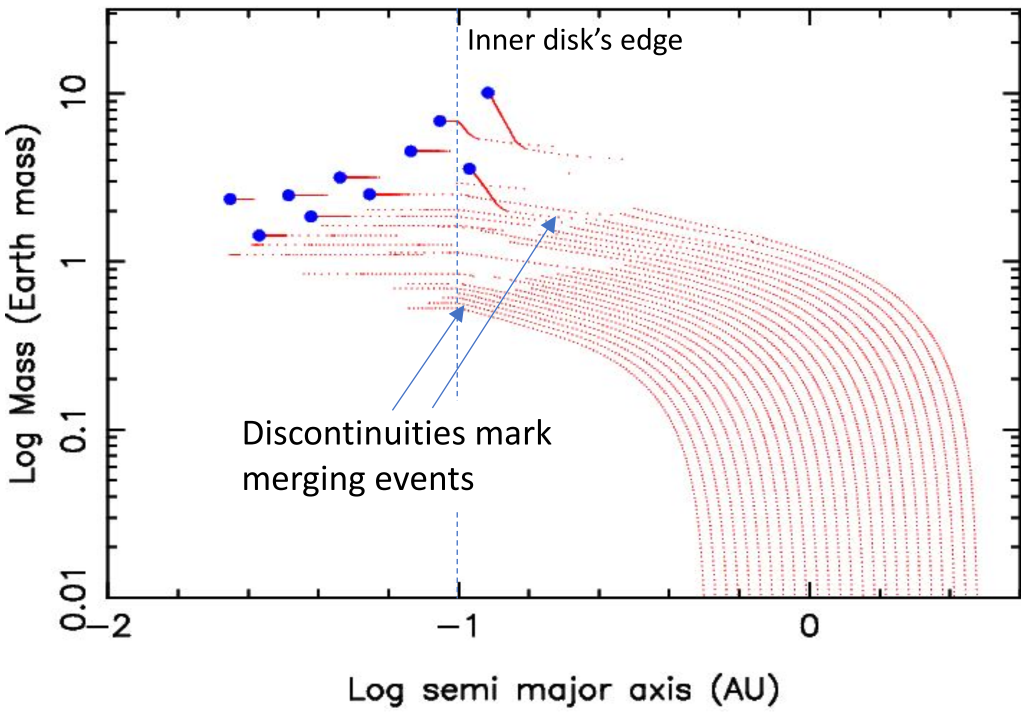
t1:
snow line
wet gas
dry gas
3 AU
r
Planetesimal seeds:
ice
rocky
Particles flow:
ice
rocky

ii) The Jupiter barrier can explain why we have terrestrial planets in the Solar System and not Super-Earths (Lambrechts et al., 2019)

Integrated pebble flux = 114 M_E
Total final mass ~ 9M_E



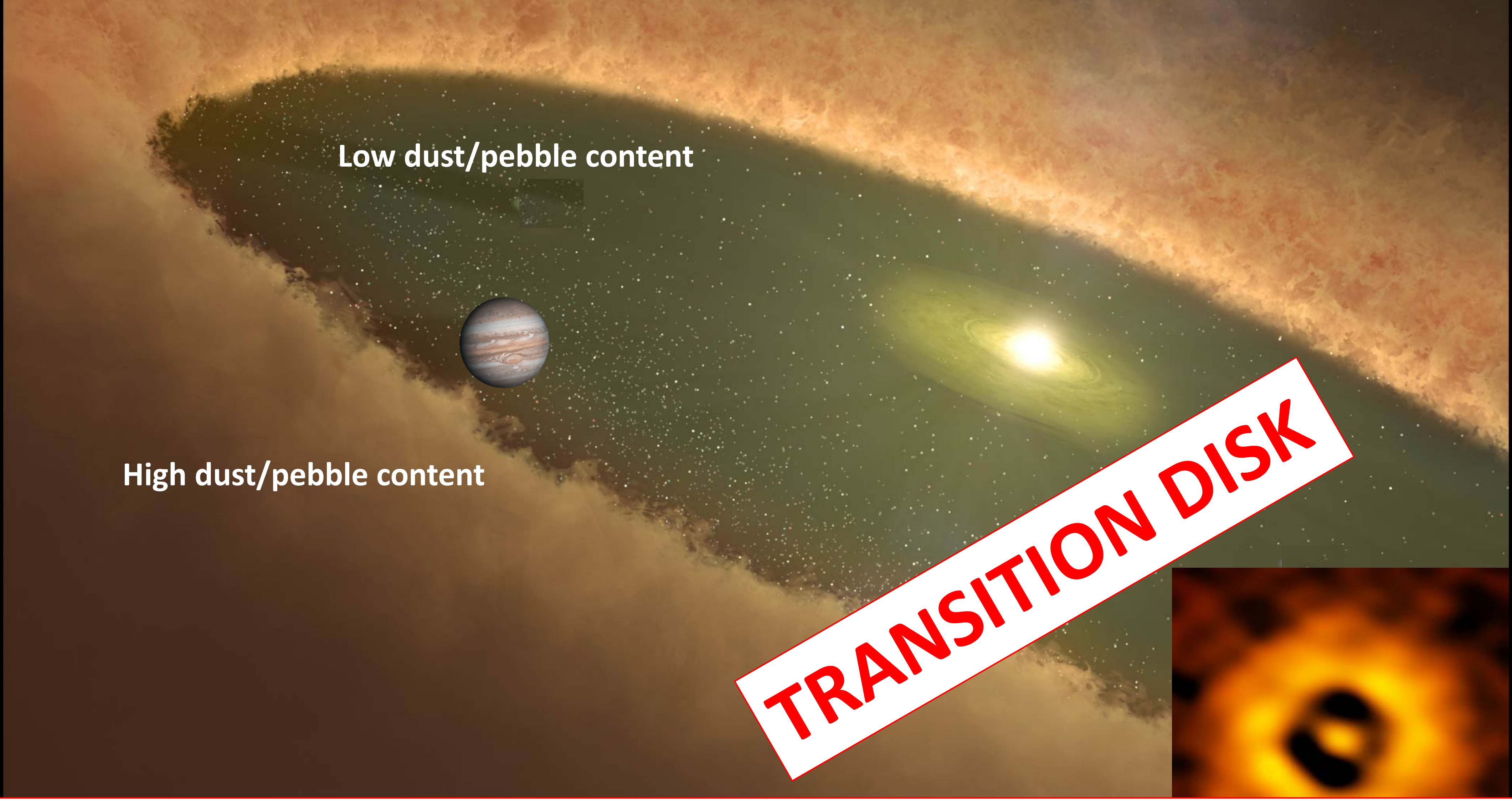
Integrated pebble flux = 190 M_E
Total final mass ~ 20-30 M_E



CONCLUSIONS

- **Cosmochemical evidence requires that the Solar System was divided in two distict isotopic réservoirs before 1My (Kruijer et al., 2017)**
- **Implies no circulation of dust larger than 100-300µm from the outer to the inner disk (Weber et al 2018, Haugbolle et al., 2019)**
- **This could have been due to the rapid (<1My) formation of a massive proto-Jupiter (30-50M_E)….**
- **….or the existence of a zonal flow, which then favored the formation of Jupiter which allowed the barrier to persist over the lifetime of the disk**
- **The existence of a barrier also explains why the inner disk remained dry despite cooling below T_{ice}**
- **The Jupiter barrier probably regulated also the mass growth of planetary embryos in the inner Solar System and hence the final masses and locations of the terrestrial planets (Lambrechts et al., 2019).**

Artist's view of the Jupiter's dust barrier



The Solar System became a transition disk within 1 My