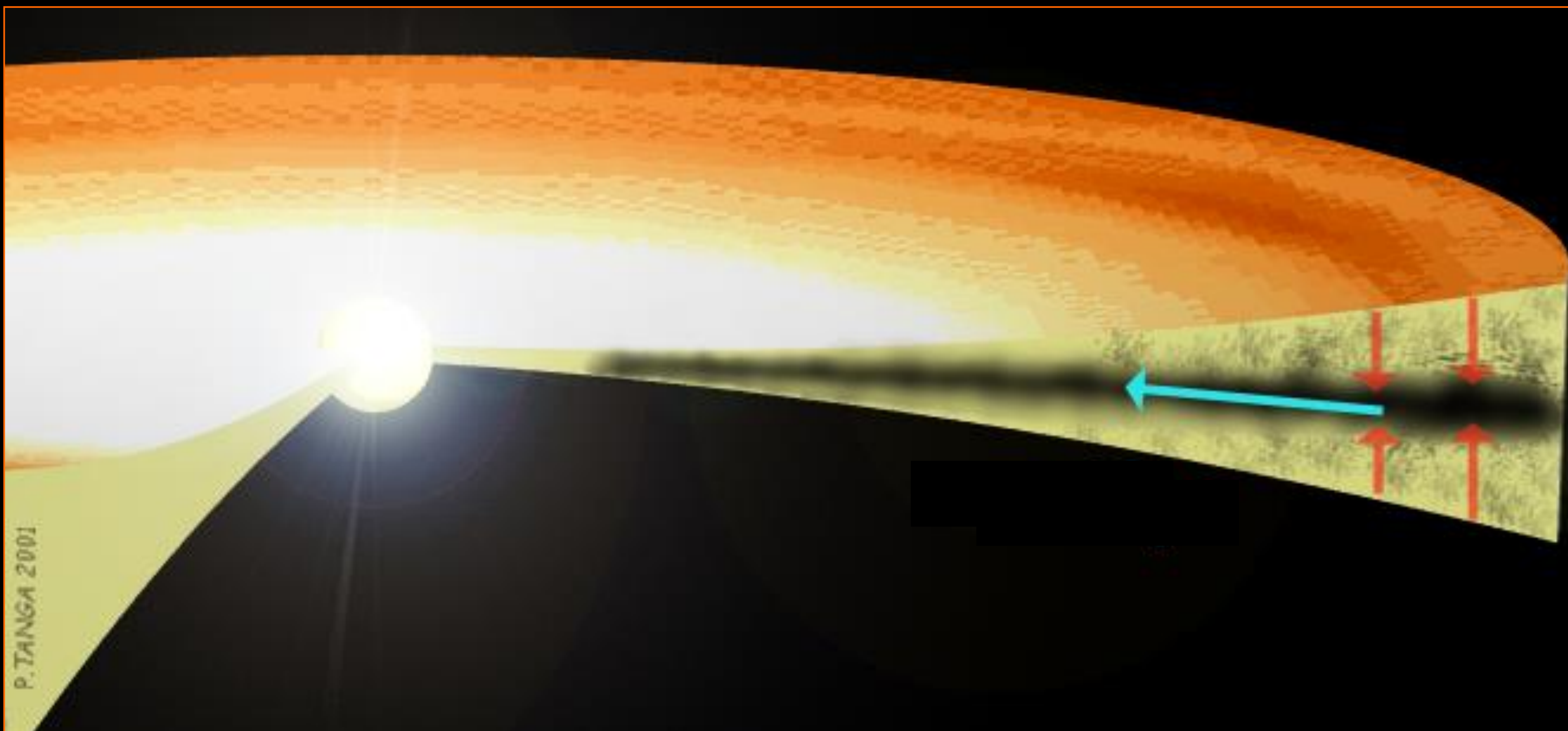
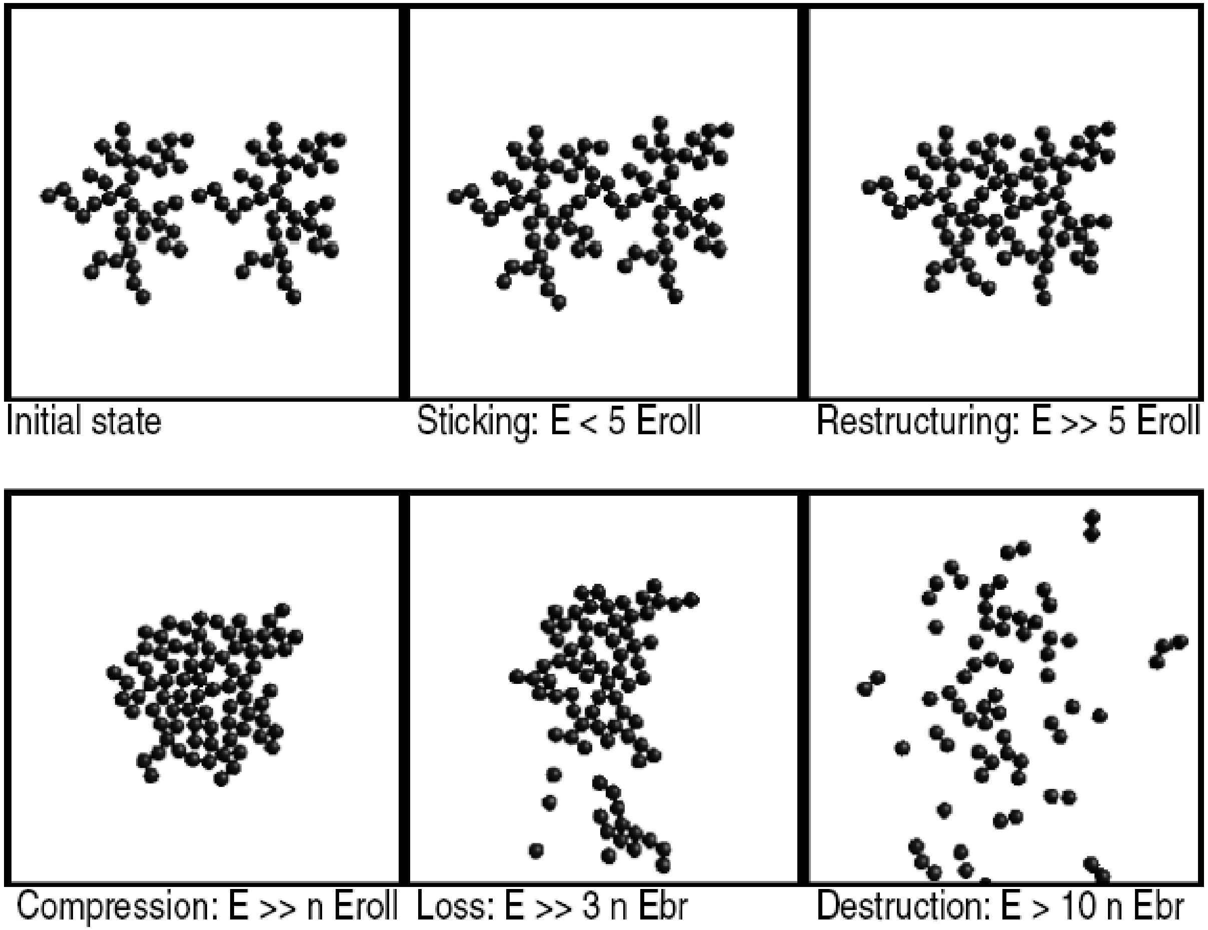
Solar System formation and evolution: dynamical models and cosmochemical implications

Alessandro Morbidelli, OCA, CNRS, Nice, France

TWO STEPS TO PLANET ACCRETION:
1) PLANETESIMAL FORMATION



Aggregate-aggregate collisions: results



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

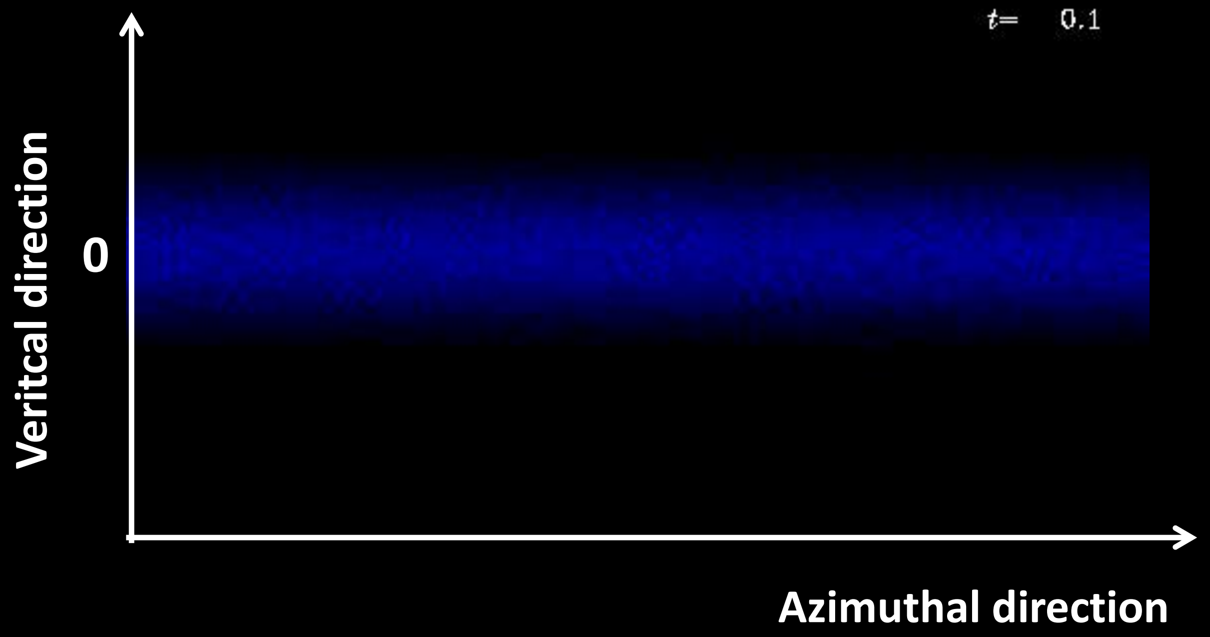
A mm-size bouncing barrier for silicates

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,….)

Particle clumping in the disk due to

1) Sedimentation on the mid-plane: Kevin Helmolt instability
2) Radial drift: streaming instability



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

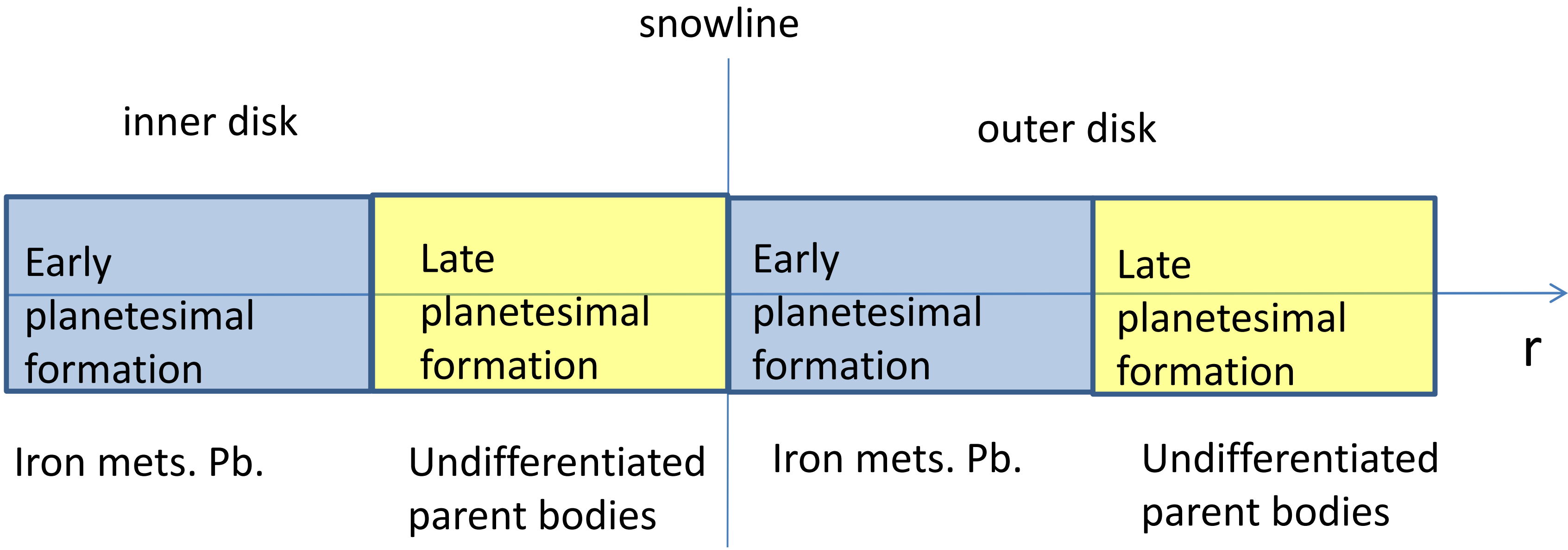
Clumps of particles that are dense-enough can become self-gravitating, and then contract to form a compact planetesimal (sizes 50-1,000 km?)

Clumping is possible only if the initial particle/gas ratio is "large enough"

This condition can be achieved due to

1) Radial pile-up of particles (rapid but local process)
2) Removal of gas due to photoevaporation (late and global process)

Thus in principle we can expect a situation like this:



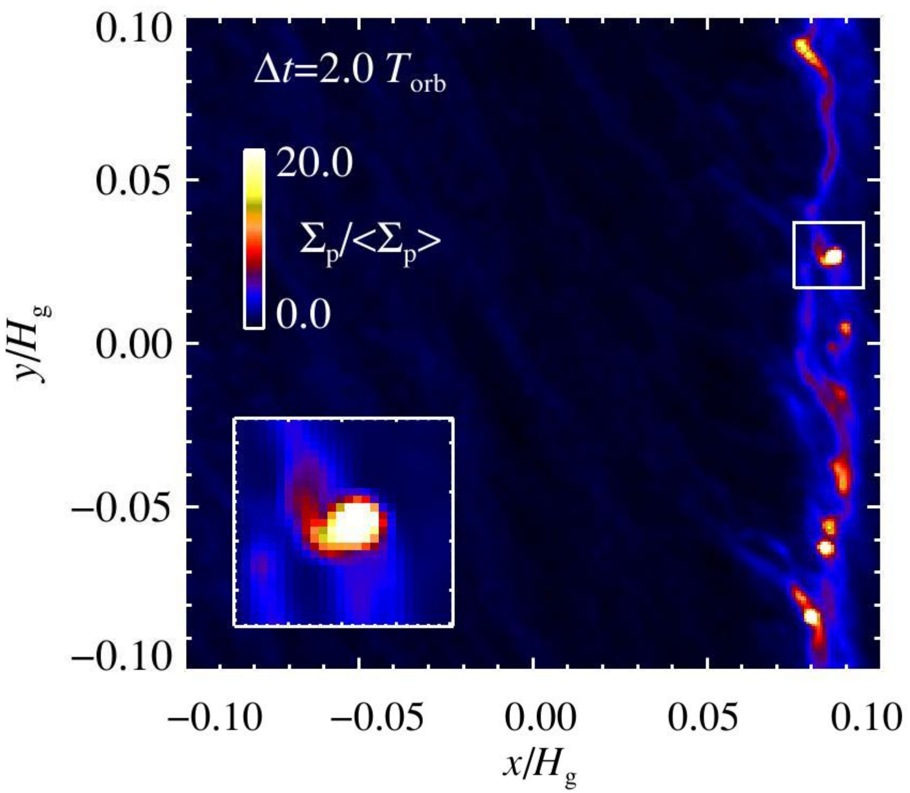
Two-steps to planet formation: 2) from planetesimals to proto-planets

The largest planetesimals keep growing by accreting individual particles (pebble accretion)

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

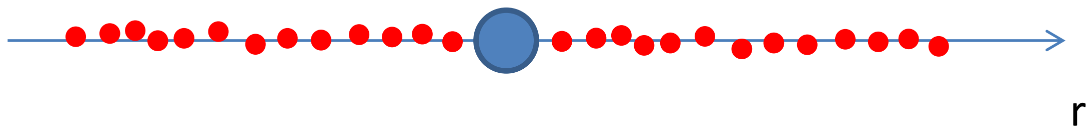
Thus they can still accrete pebbles flowing by them in the disk

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



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

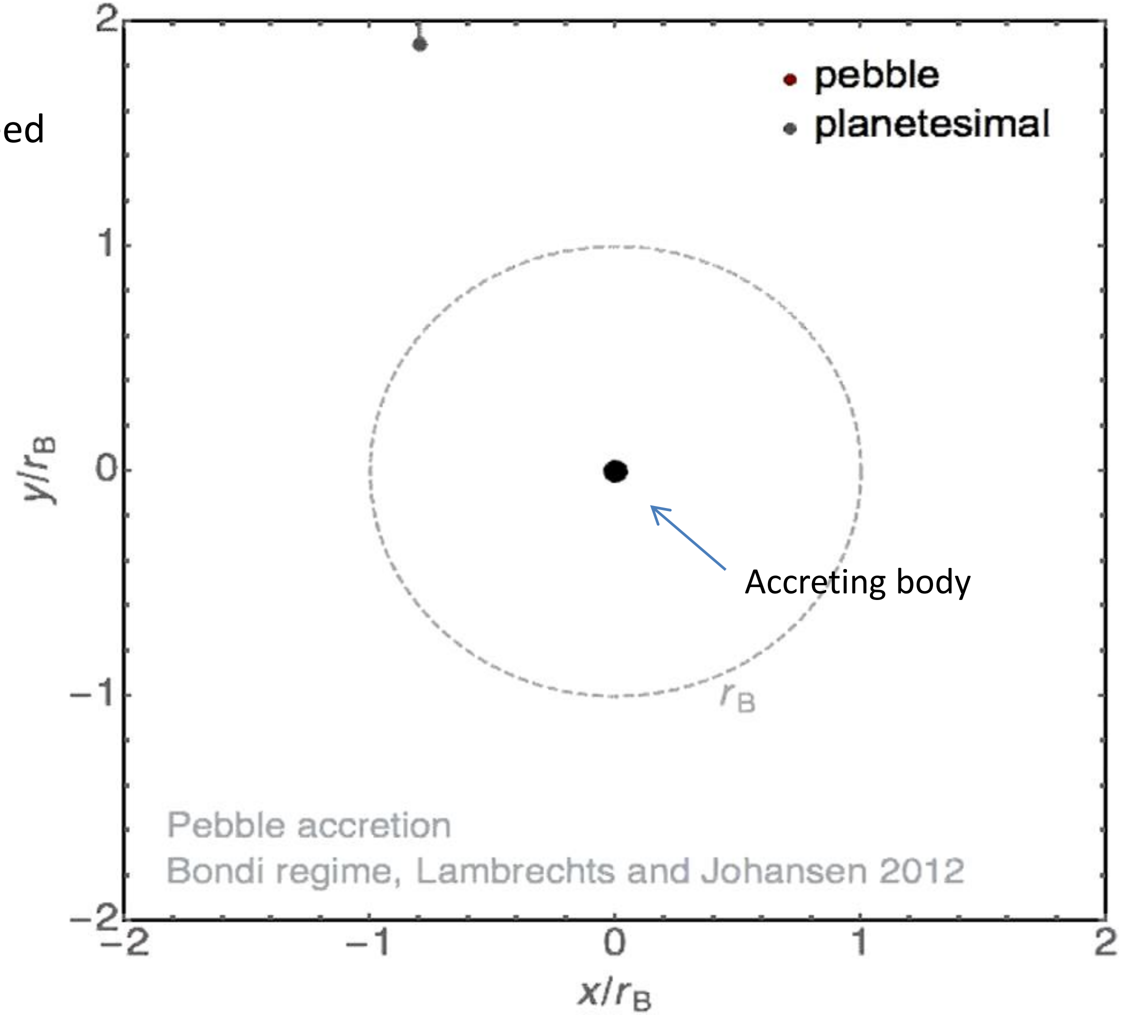
I) No isolation



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

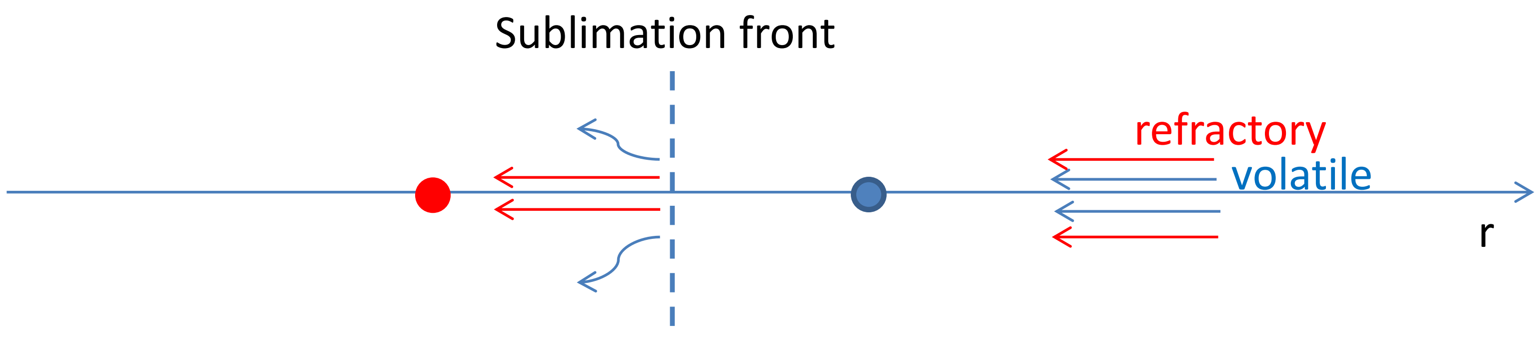
$$r_B = \frac{GM_c}{\Delta v^2}$$

relative speed



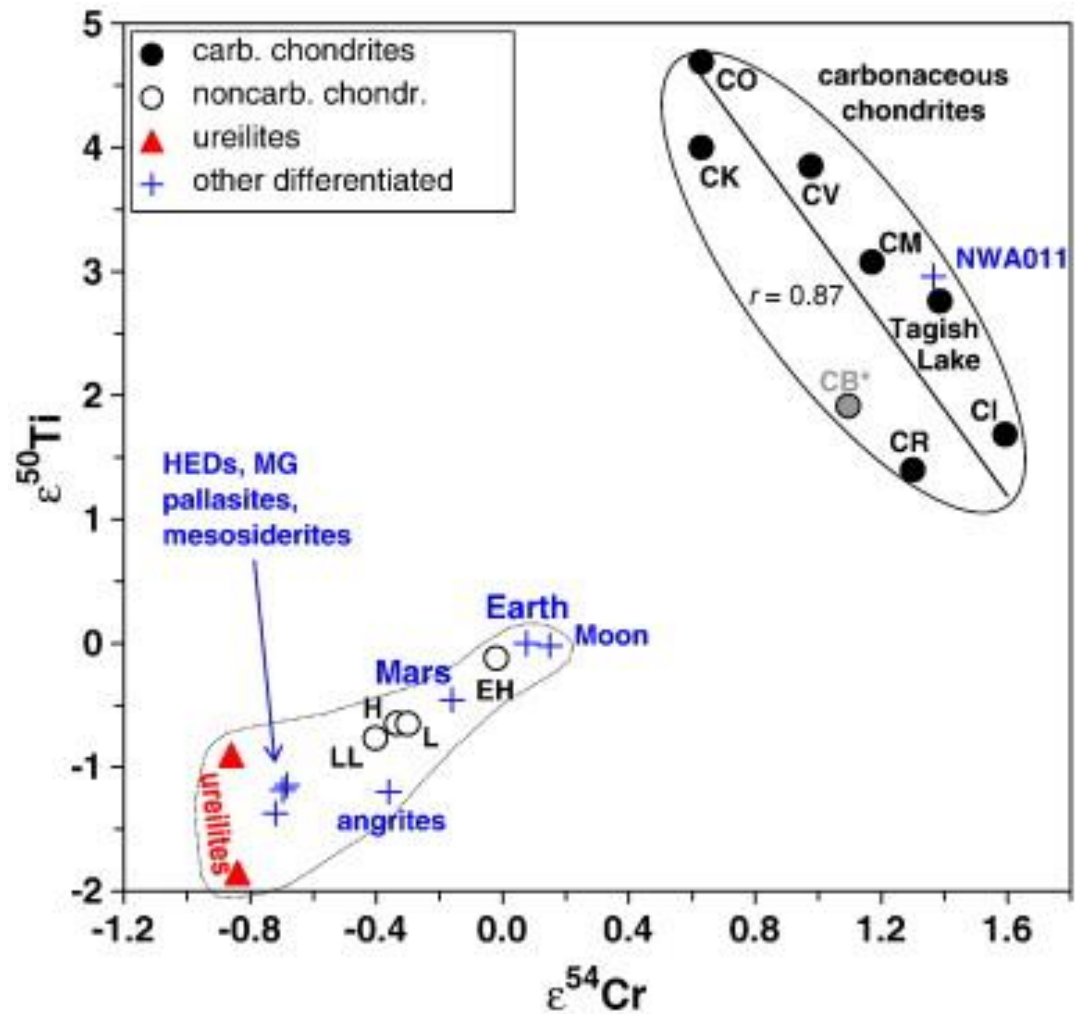
Implications

- There is no longer the concept of local material. Each body accrete material coming from the entire disk beyond its orbit.
- But this does not mean that all bodies should be chemically the same. – evaporation fronts lead to chemical fractionation vs. volatility



- However, there shouldn't be distinct isotopic reservoirs for refractory elements

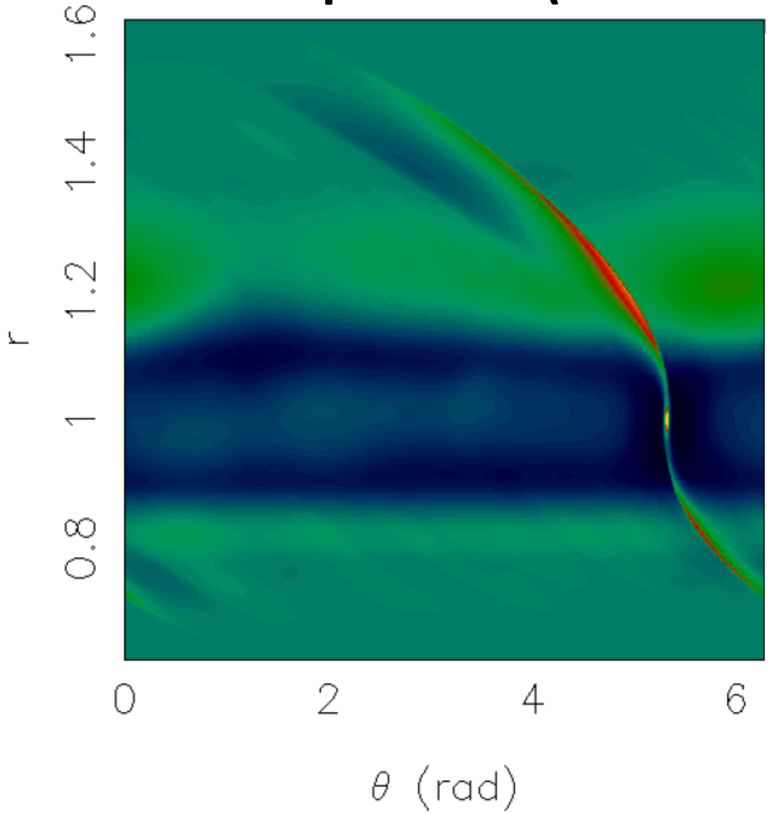
But there are distinct isotopic reservoirs in the Solar System….

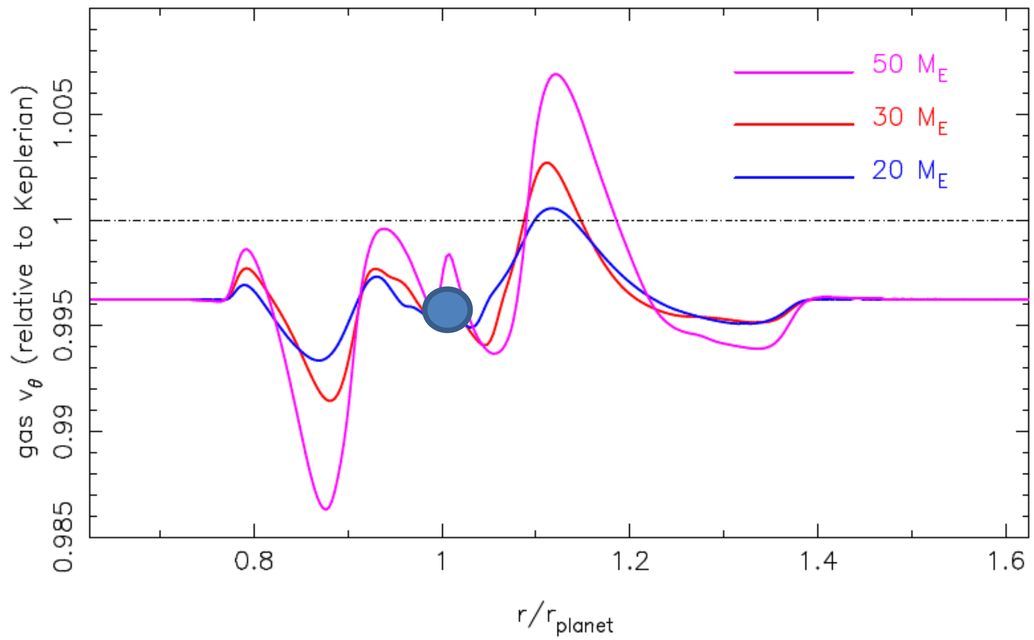


Modified from P. Warren (2011)

THE JUPITER BARRIER

When a protoplanet reaches a mass of ~ 20 Earth masses, it cuts off the flow of condensed particles (of size > 100microns) towards the inner disk

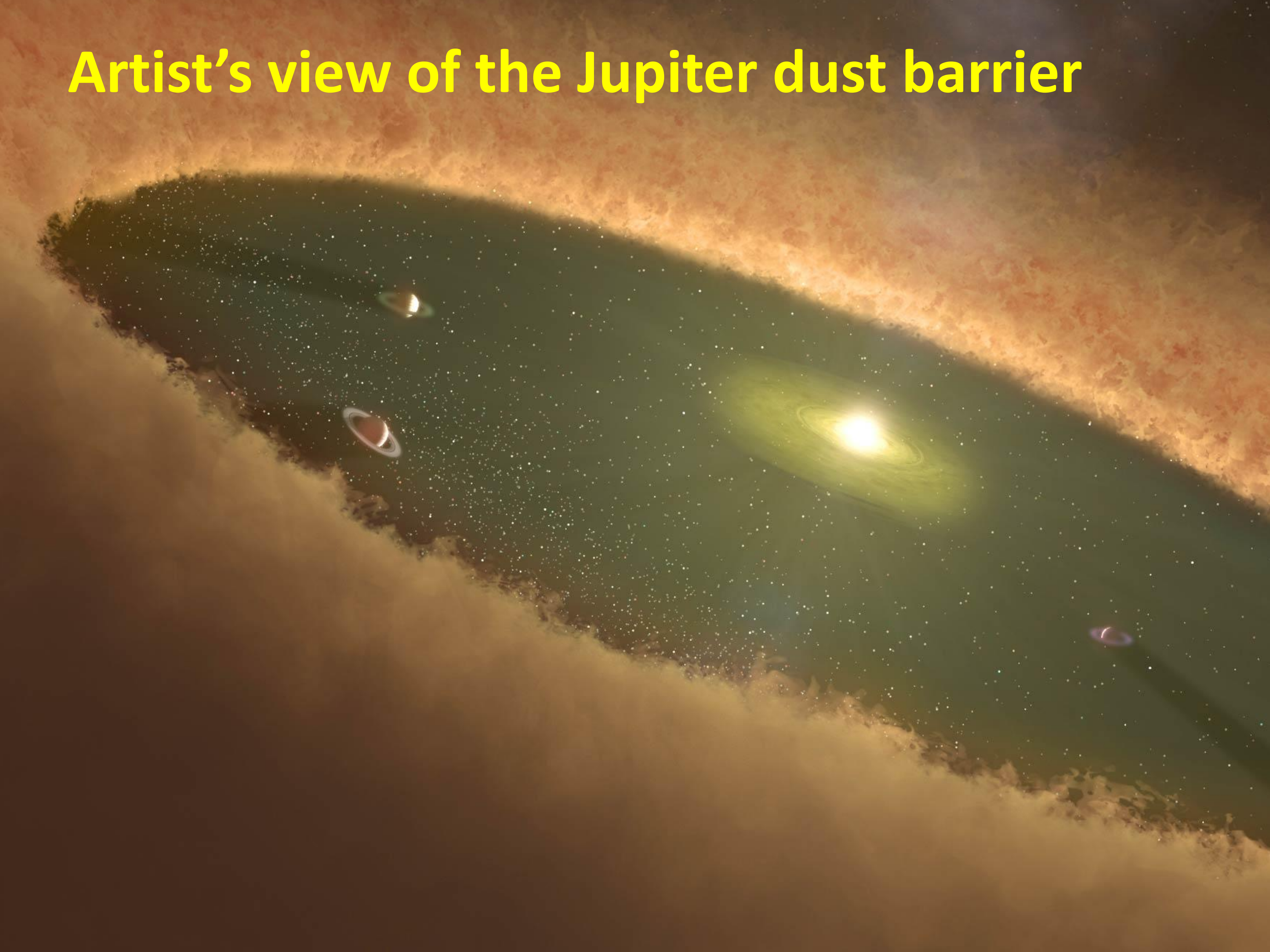


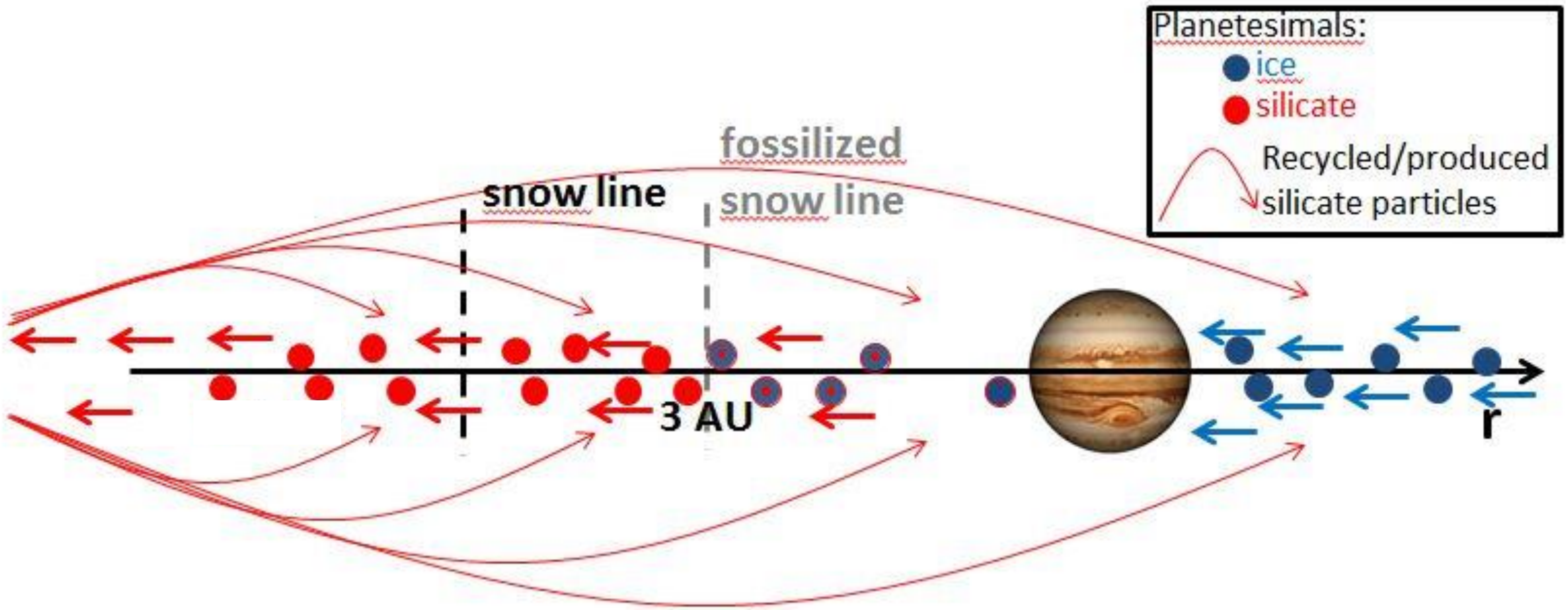


Morbidelli and Nesvorny, 2012
Lambrechts, Johansen and Morbidelli, 2014

The growth of proto-Jupiter is the key to understand the separation of distinct reservoirs in the Solar System (Morbidelli et al., 2016)

Artist’s view of the Jupiter dust barrier



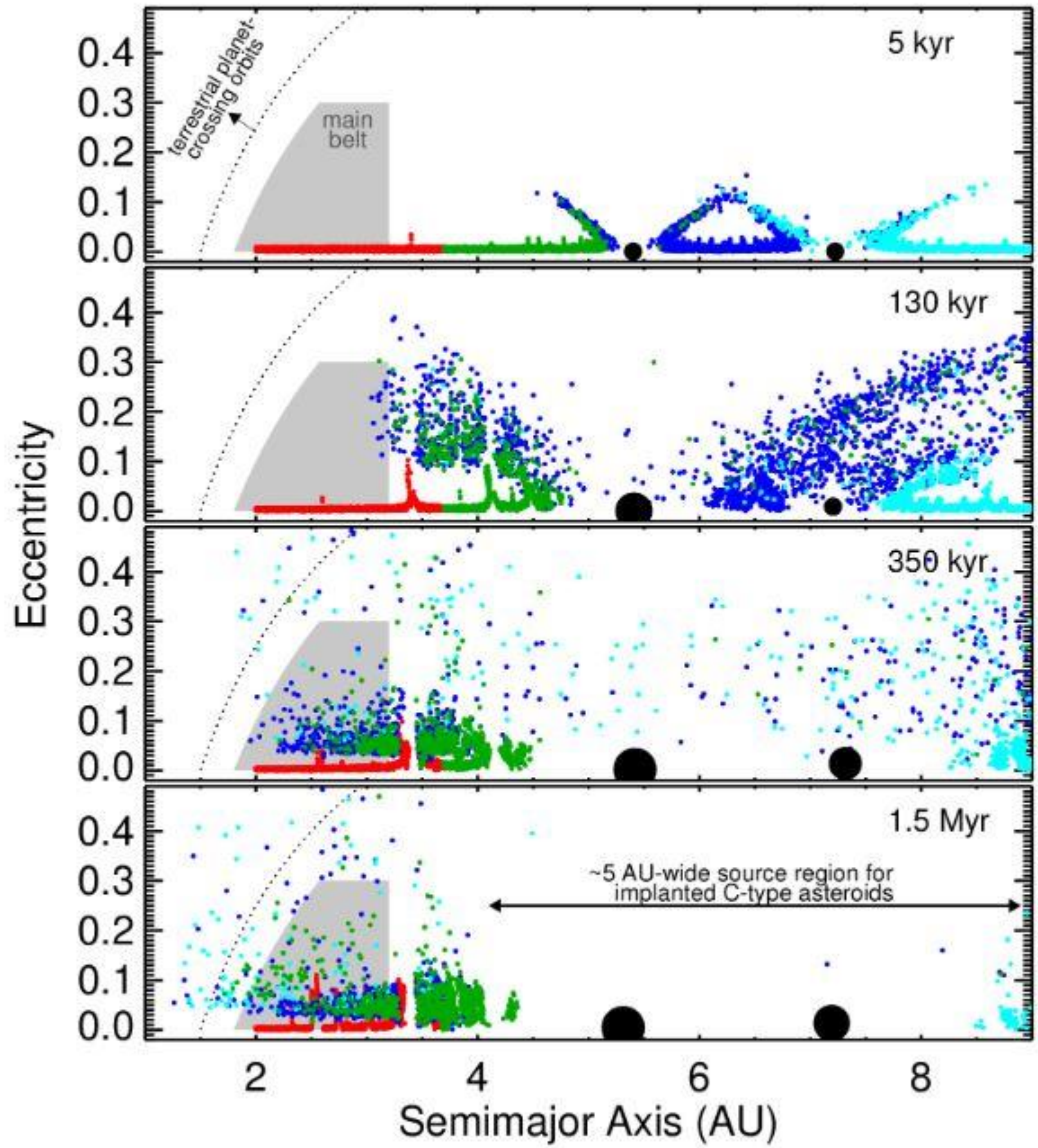


The appearance of a proto-Jupiter would stop the flow of pebbles into the inner disk, with several consequences:

- **Planetesimals inside the orbit of proto-Jupiter accrete from different reservoirs of material (outer disk pebbles vs. recycled material in the inner disk)**
- **Appealing to explain drastic differences between ordinary and carbonaceous chondrites (not just water content, but chondrule types, CAIs, isotope ratios…)**
- **According to isotope chronology, the separation of reservoirs should have happened within the first My (Kruijer et al., 2017)**
- **The formation of Jupiter keeps the inner system water poor even after that it has cooled below 200K (fossilization of the snowline: Morbidelli et al., 2016)**

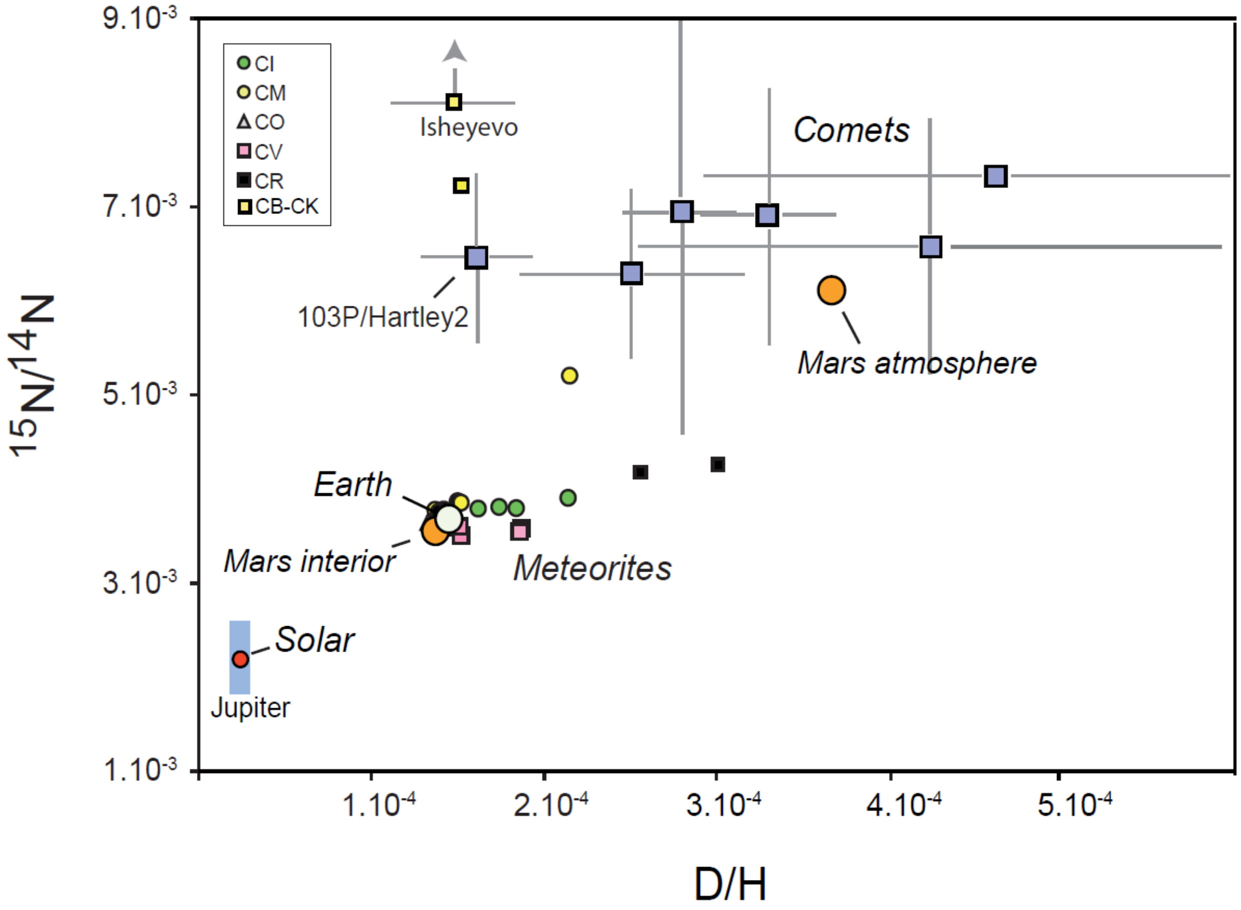
Planetesimals formed beyond Jupiter (i.e. carbonaceous-chondritic bodies) could be injected into the asteroid belt during the growth of Jupiter (Raymond and Izidoro, 2017) and/or its migration (Walsh et al., 2011; O'brien et al., 2014).

The process of scattering of carbonaceous material towards the inner solar system is also responsible for bringing water to the (growing) terrestrial planets

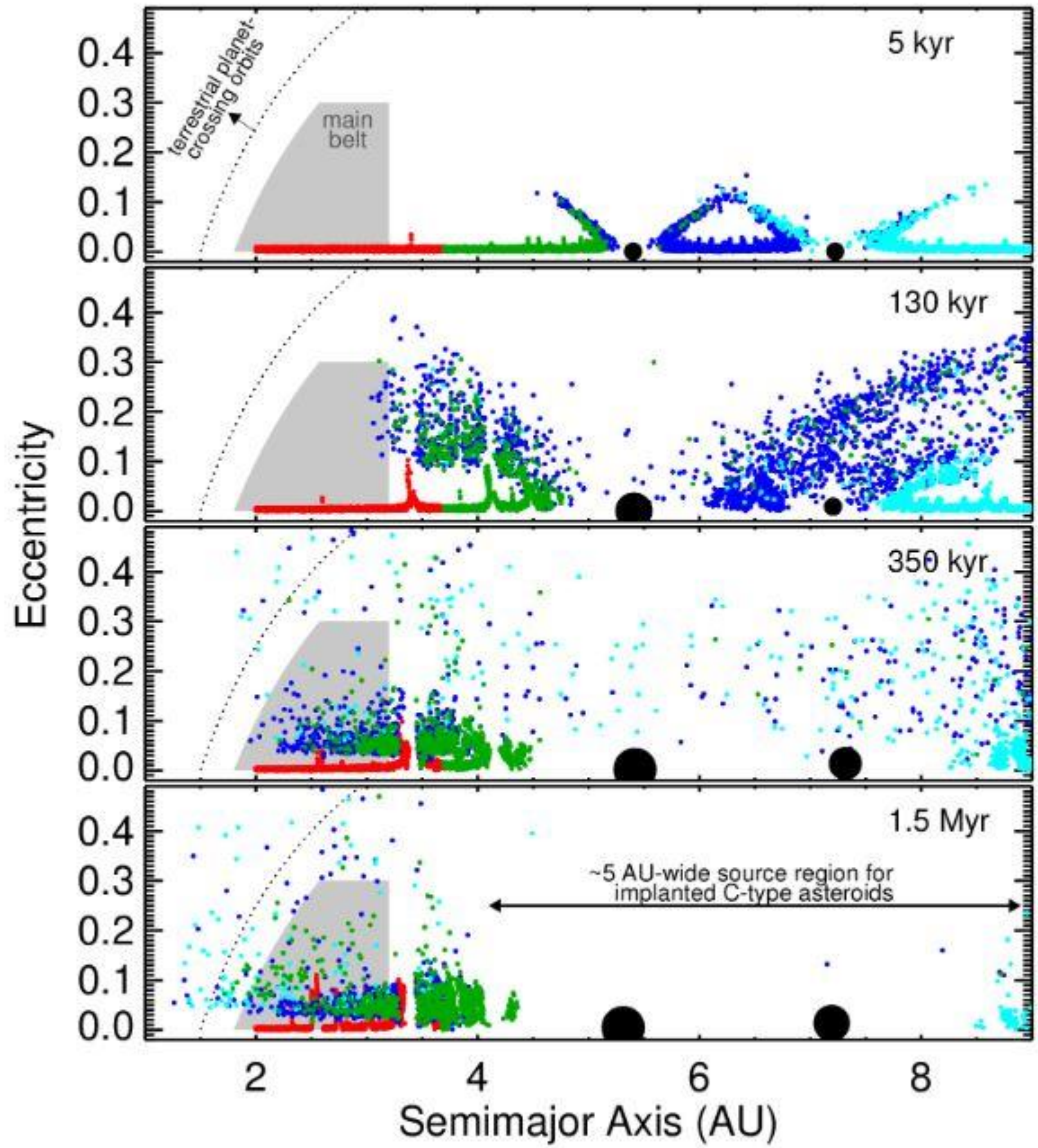


Raymond and Izidoro, 2017

Isotopic analyses confirm that carbonaceous asteroids are the most likely source of water and nitrogen for the Earth

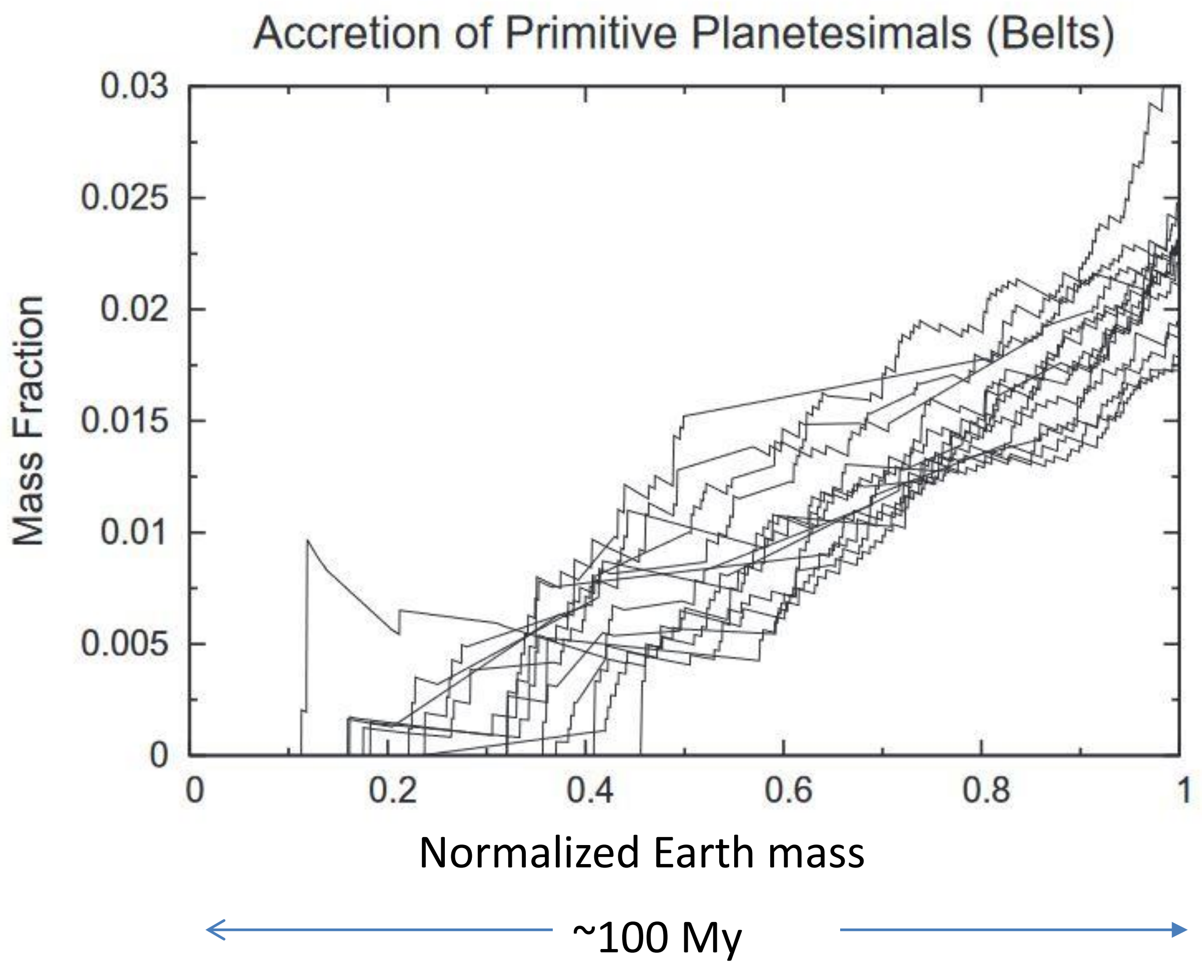


Because the scattering of carbonaceous asteroids towards the inner solar system is contemporary to Jupiter's growth/migration the water was available to the Earth early, during its formation



Raymond and Izidoro, 2017

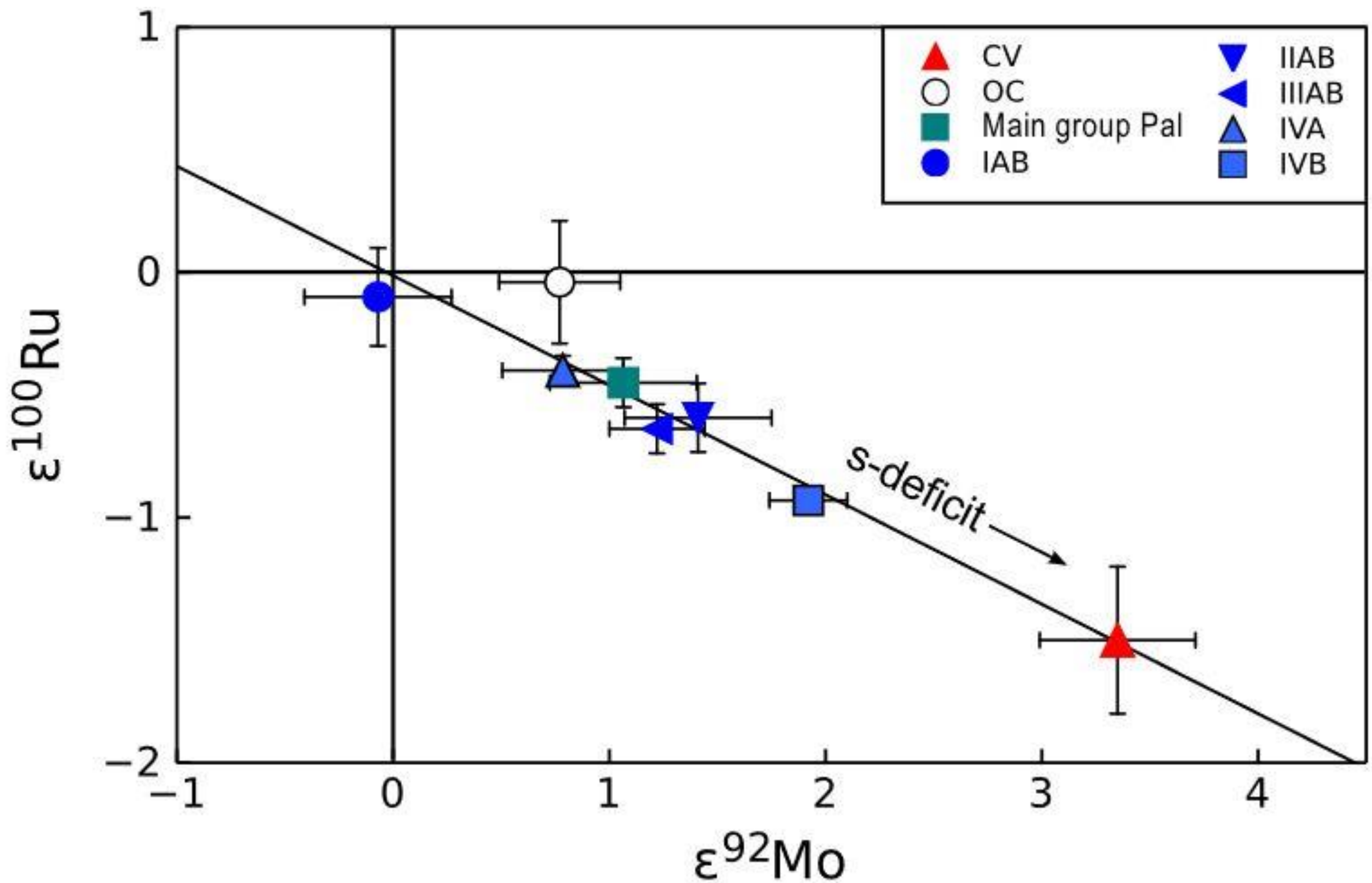
The accretion of water does not happen during the Late Veneer. The predominant amount of water is accreted during the main accretion phase of the Earth



O'Brien et al., 2014

The Ru-Mo isotope correlation implies that the Late Veneer had to have the same composition of the material that accreted the bulk of the Earth

(Dauphas et al., 2004; Burkhardt et al., 2011; Dauphas, 2017)



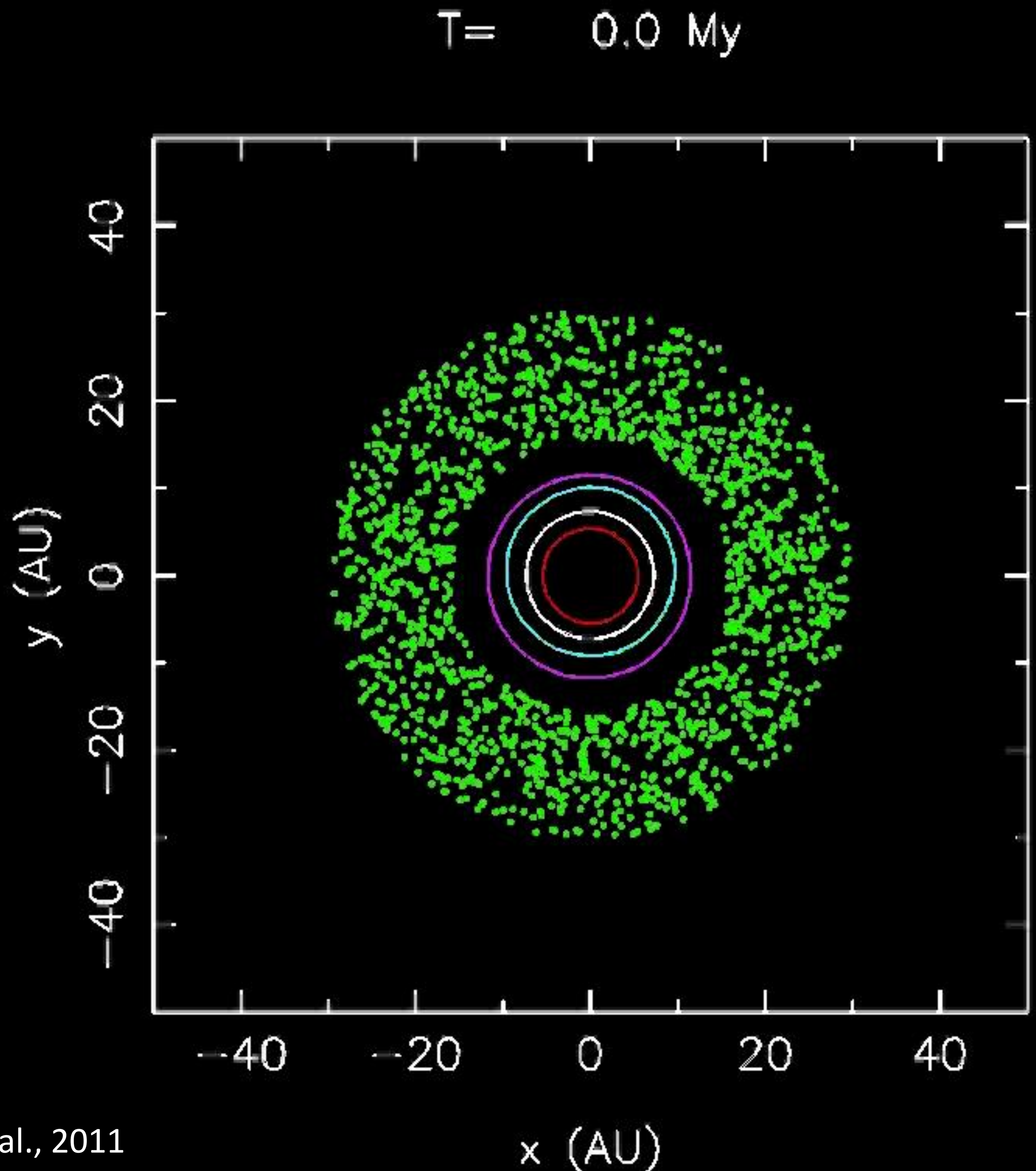
Burkhardt et al., 2011

The cometary bombardment

Definition: given that primitive asteroids (carbonaceous chondrites) could originate from beyond Jupiter's orbit, I call "comets" the planetesimals formed beyond Neptune

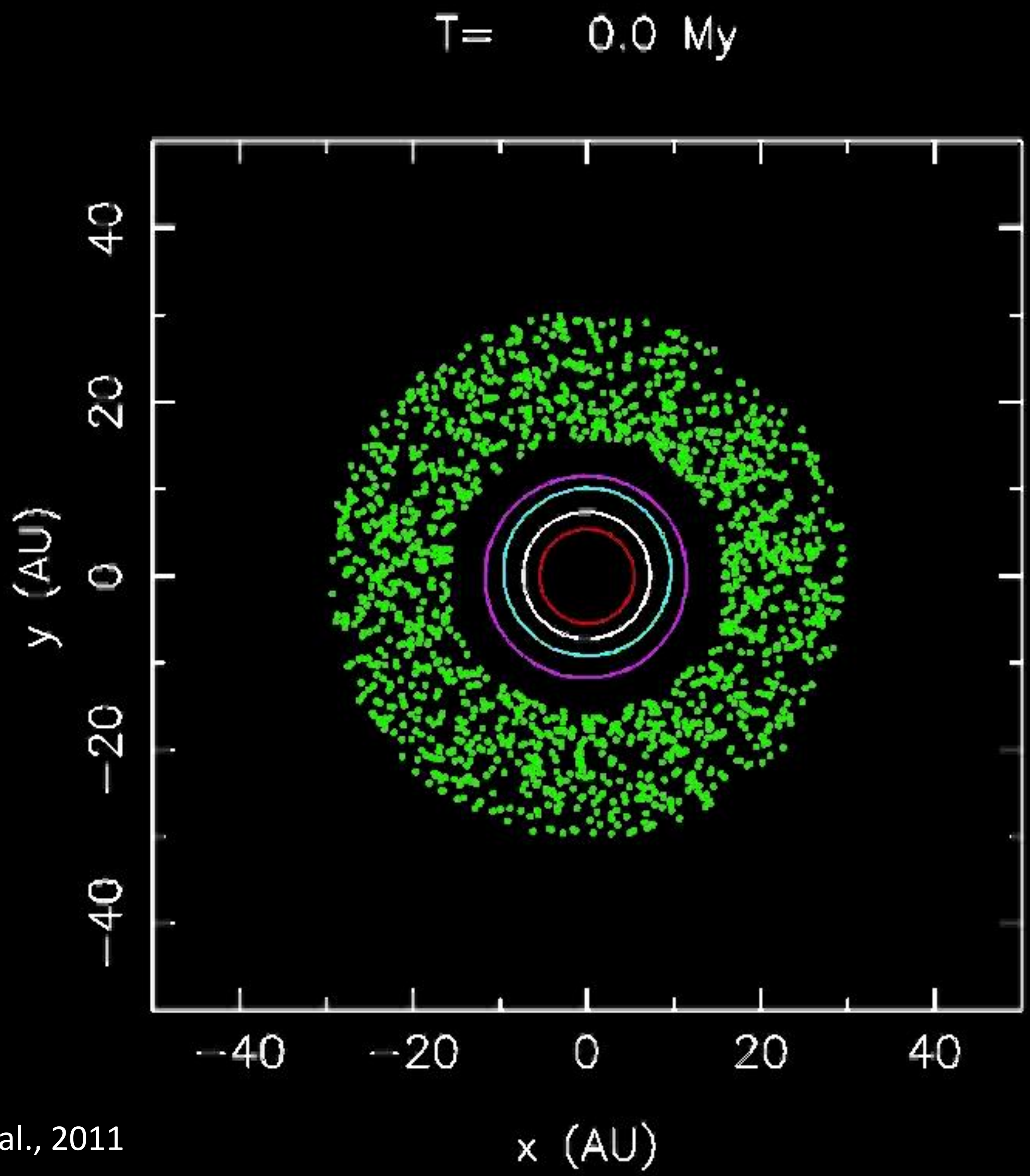
Note: there is probably a continuum of physical & chemical properties between primitive asteroids and comets (CO/CV – CM/CI – CR – Wild II – 67P....)

It is believed that at the end of the gas-era of the protoplanetary disk, the giant plant orbits were closer to each other and more circular than now, as a result of giant planet migration



Morbidelli et al., 2007; Levison et al., 2011

Multiple Solar System features give evidence for a Giant Planet Instability (i.e. THE NICE MODEL)



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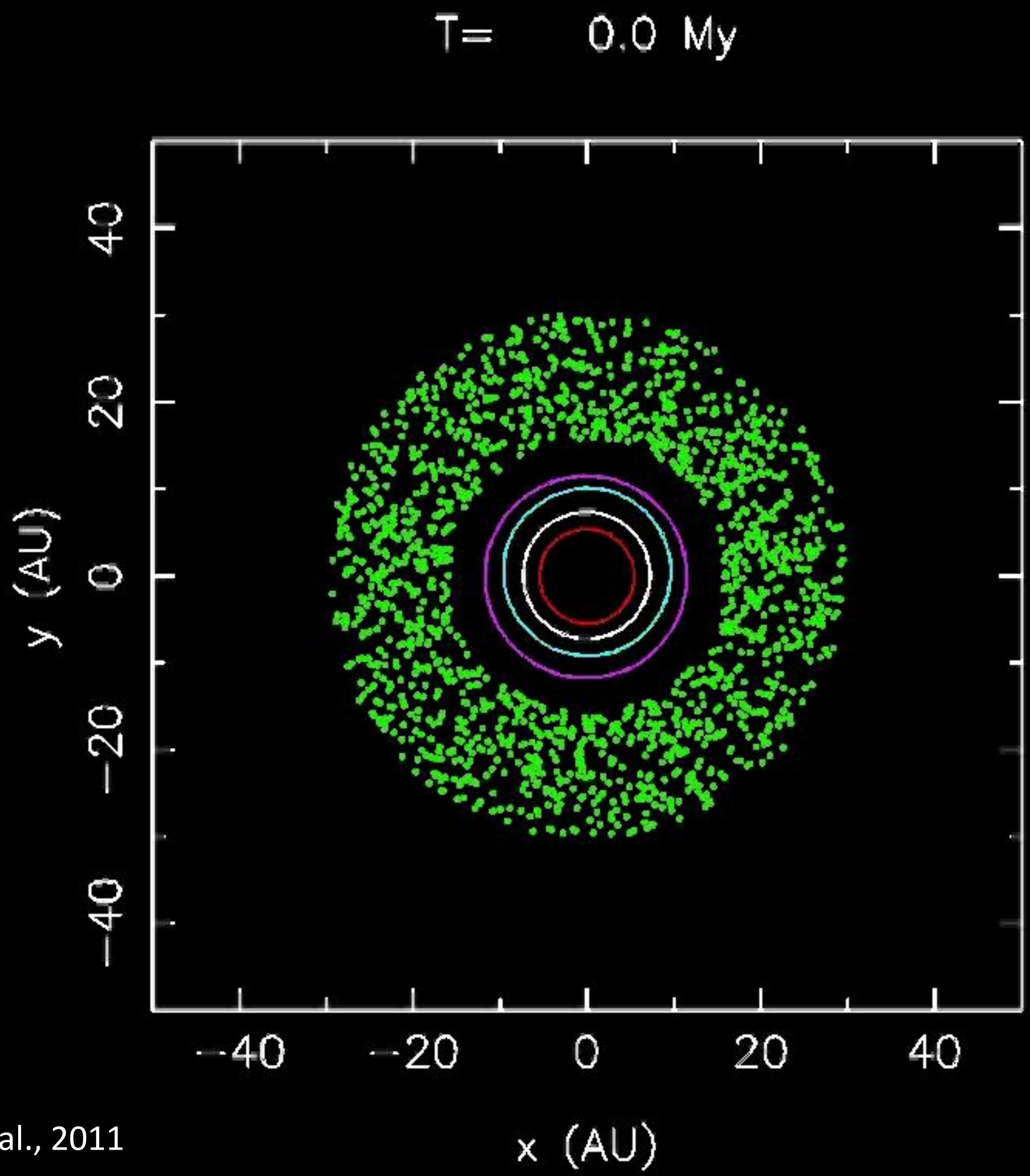
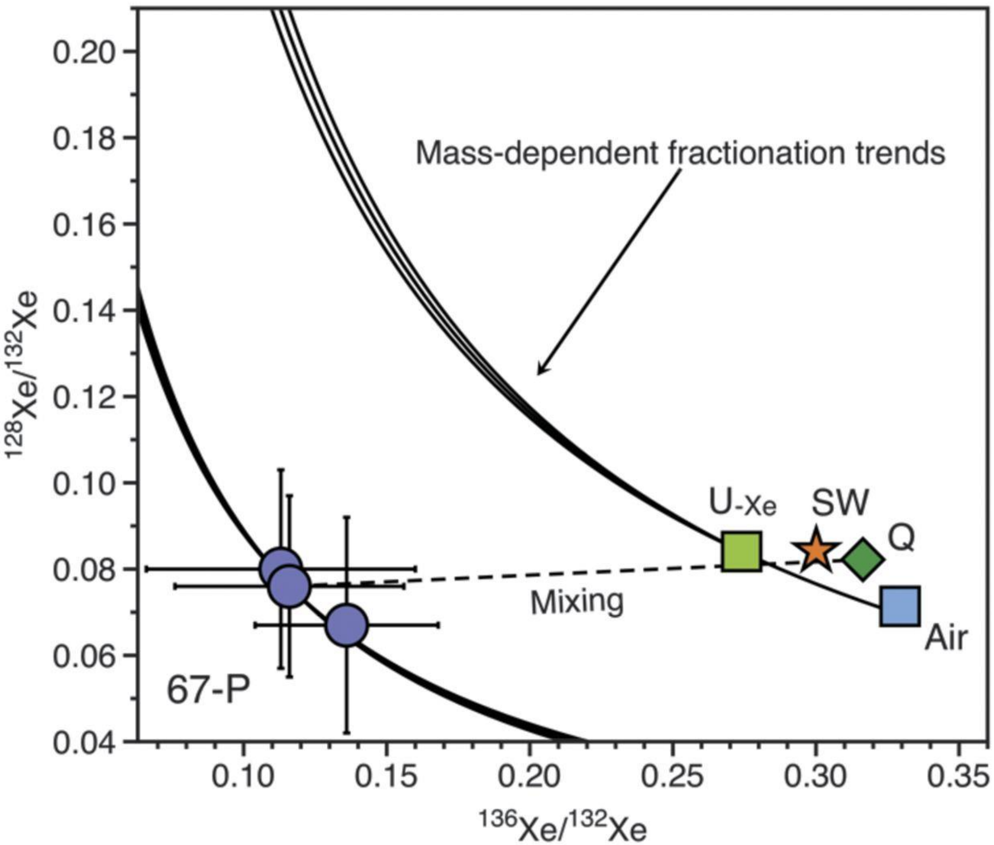
Multiple Solar System features give evidence for a Giant Planet Instability (i.e. THE NICE MODEL)



But the timing of the instability is NOT constrained by the dynamics

Morbidelli et al., 2007; Levison et al., 2011

Evidence for a cometary bombardment on earth: Xenon



Geochemists (Pepin, 1991; Pepin and Porcelli, 2002; Avice et al., 2017) had established that the escape-corrected isotope composition of the atmosphere, denoted U-Xe. is distinct from the mantle source, which is *chondritic* « Q » Xe (Caracausi et al. 2016).

<u>But the origin of U-Xe was unknown</u>

With Rosina measurements, mixing 22 ± 5% (1σ) cometary (67P/C-G) Xe with Q-Xe reproduces the composition of U-Xe ! (Marty et al., 2017)

This requires that the Earth accreted ~10^{22}g of comets in very good agreement with what is predicted by the dynamical model of cometary bombardment

The absence of U-Xe signature in the Earth's mantle implies that the cometary bombardment occurred towards the end of Earth formation, possibly during the Late Veneer

CONCLUSIONS

- **Pebble clumping via the KH or S-instability is the main mechanism leading to the formation of planesimals**
- **Pebble accretion, provided the pebble flux is high enough, is an effective mechanism to grow planetesimals up to protoplanets**

The formation of proto-Jupiter governed the subsequent formation of the Solar System

- ✓ **Because of the Jupiter barrier, bodies inside and outside the orbit of Jupiter formed from different reservoirs of material → isotopic dichotomy among carbonaceous and non-carbonaceous meteorites**
- ✓ **Inner Solar System bodies could not accrete icy pebbles from the outer disk even when the temperature dropped below ice sublimation**
- ✓ **Water was acquired by the terrestrial planet from carbonaceous asteroids scattered by Jupiter into the inner Solar System**
- ✓ **The Earth accreted water all along its growth: not as a late veneer**
- ✓ **A final giant planet instability shaped the current structure of the outer Solar System, causing a cometary bombardment of the terrestrial planets**
- ✓ **Xenon isotopes confirm that this bombardment occurred, as expected. Negligible for water, substantial for noble gasses (organics?)**
- ✓ **This bombardment occurred towards the end of the Earth's formation (preservation of complex organics?)**