From pebbles to planets
The story of the Solar System

Seth Jacobson

Observatoire de la Côte d’Azur

Outline

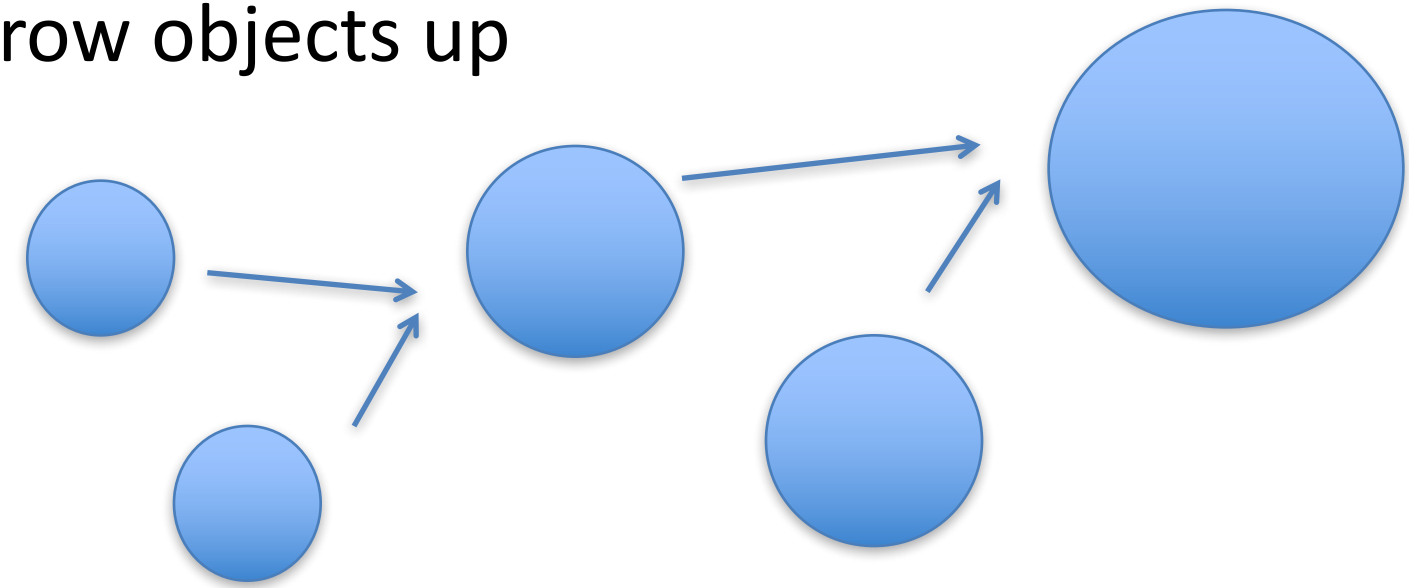
Step 1 : Pebbles to Planetesimals

Step 2 : Planetesimals to Embryos

Step 3 : Embryos to Planets

Pairwise growth

Binary collisions between similar sized particles grow objects up



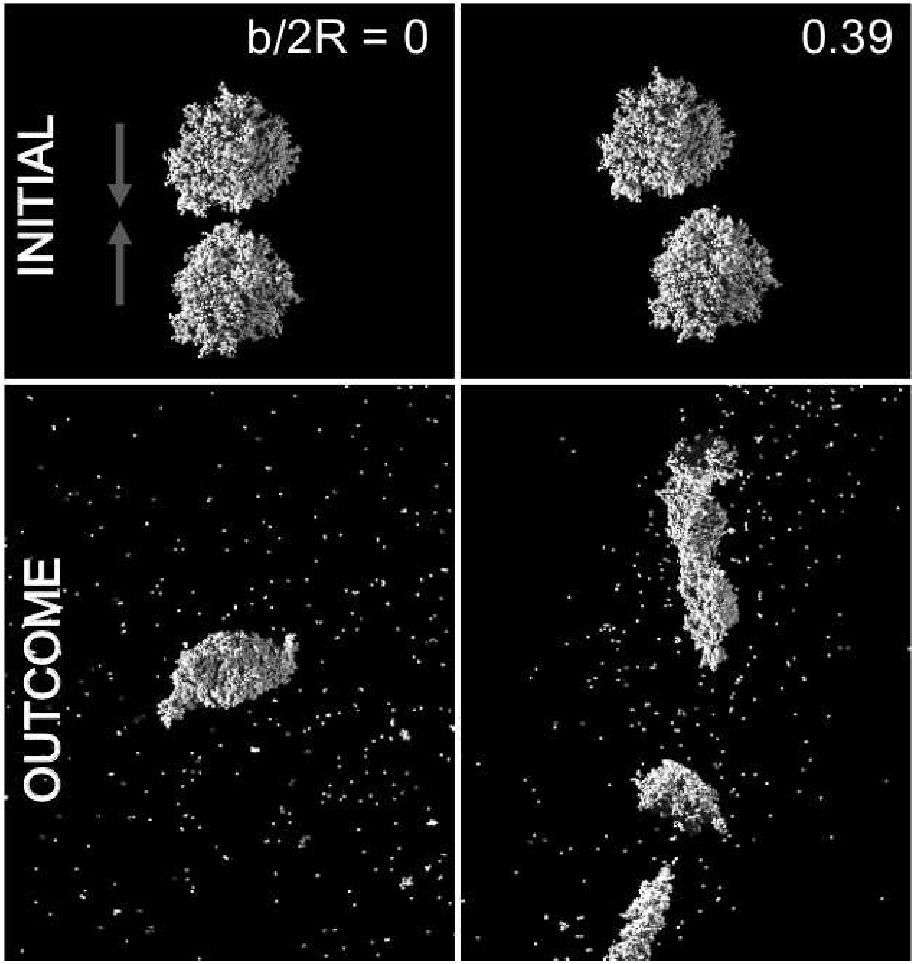
Biggest advantage is that its simple

Pairwise growth seems to work for dust

At low collision velocities (<1 m s^{-1} for silicates and <60 m s^{-1} for icy grains)

Low velocity collisions allow the efficient growth of fluffy grains

Fluffy grains can then compress as form of energy damping allowing later higher energy collisions

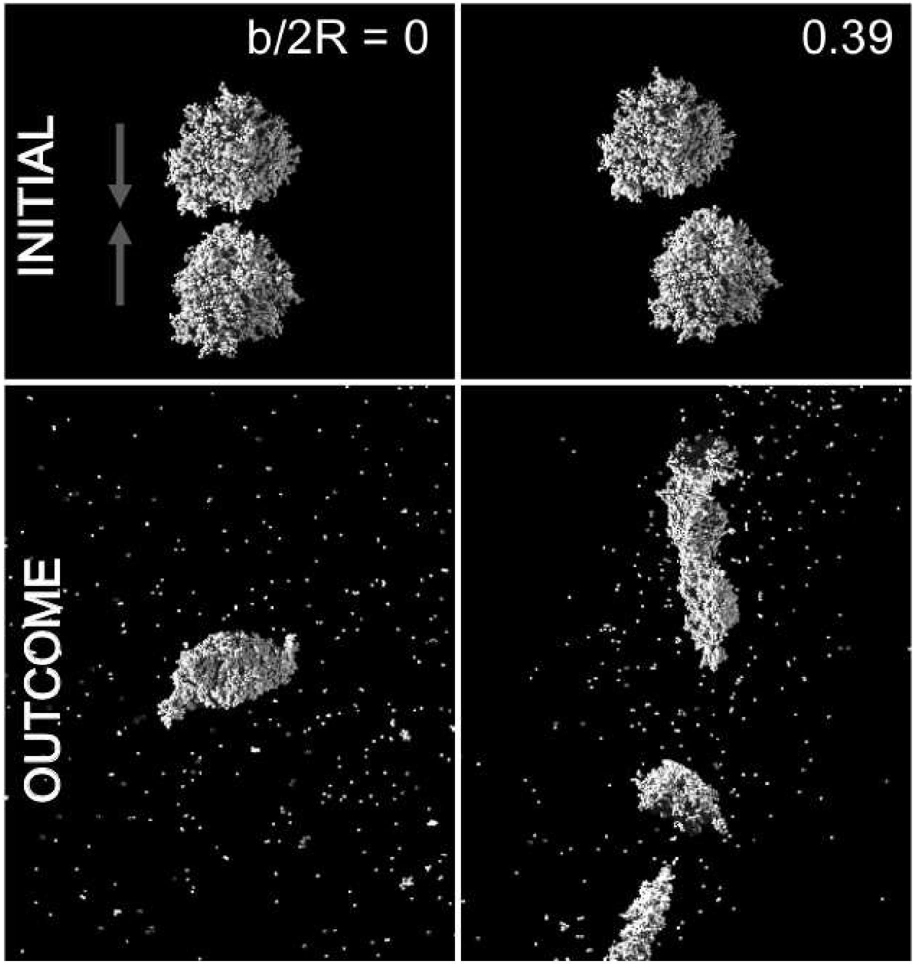


Wada et al. (2009)

Pairwise growth seems to work for dust

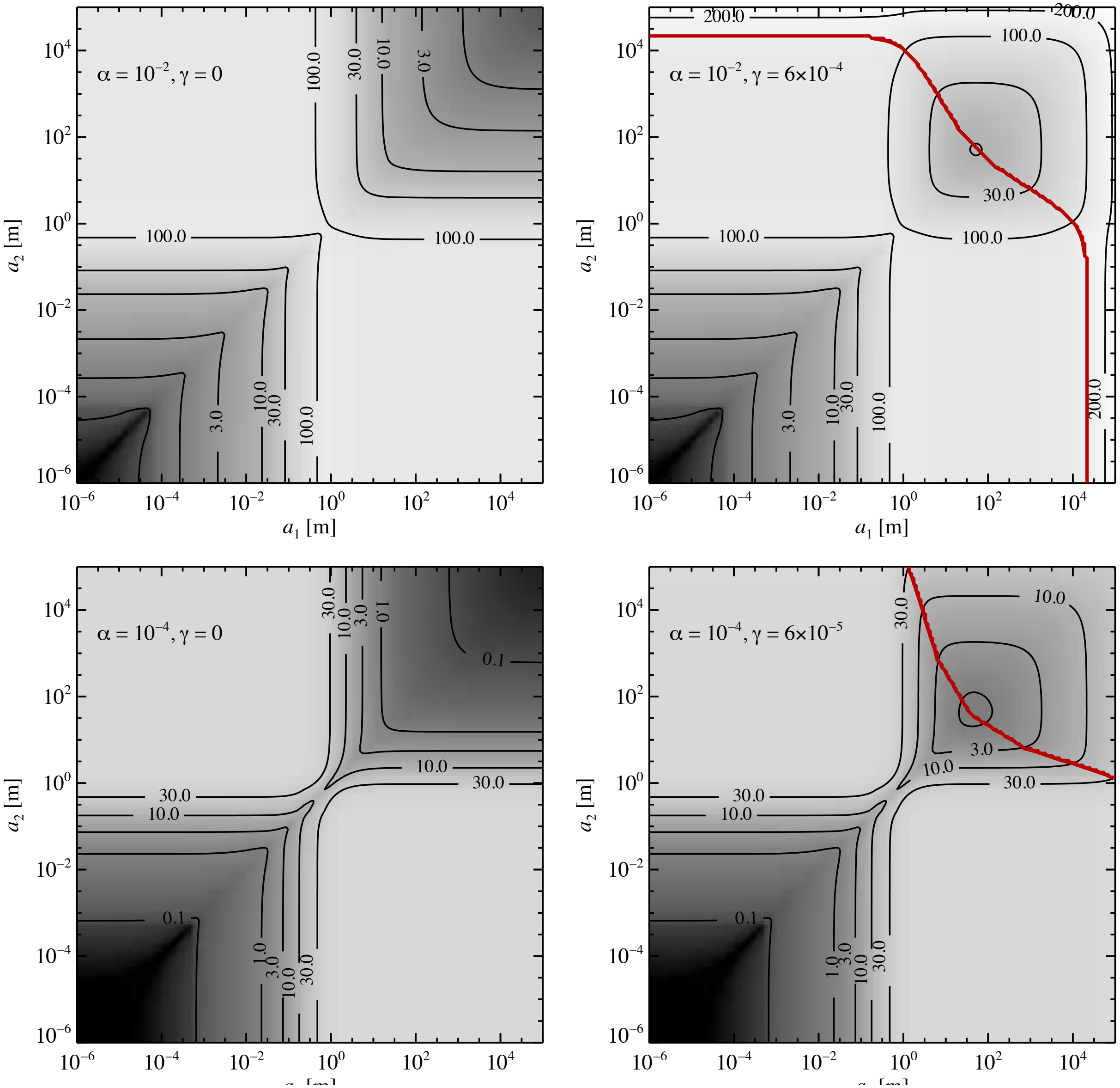
Once grains become too compact or too large, bouncing becomes a significant issue

Fragmentation can also occur if velocities in the disk get too high



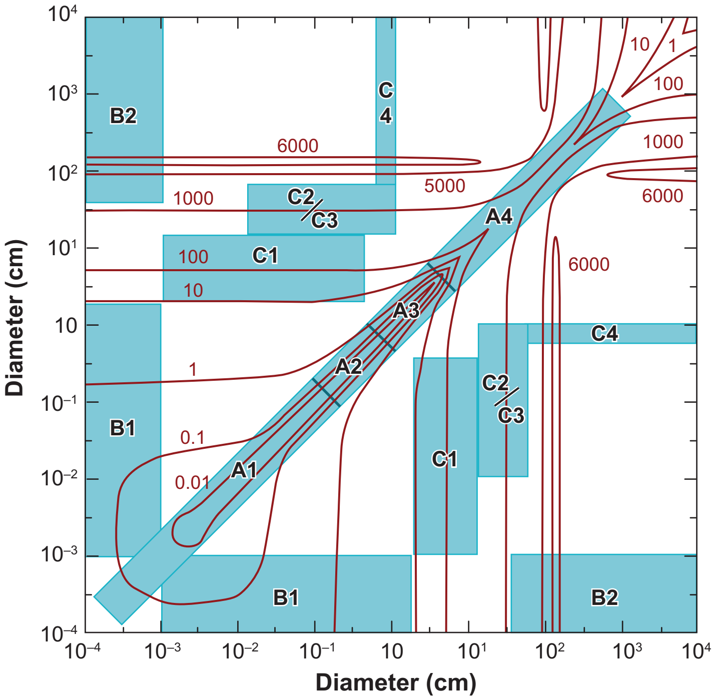
Wada et al. (2009)

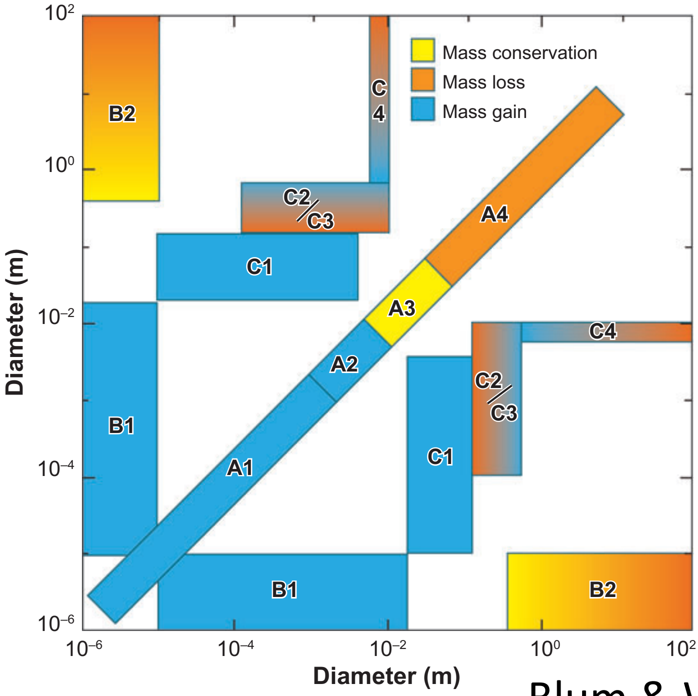
Collision velocities



The collision velocity between dust grains is determined by the turbulence of the gas, brownian motion, gravitational attraction, and differential drift

Collision velocity





Blum & Wurm 2008

The collision velocity dictates whether there is mass growth, loss or mere conservation

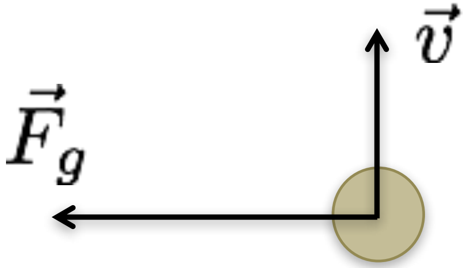
The trend is clear, larger bodies strike at higher velocities and typically lose mass

Dust growth in the MMSN model

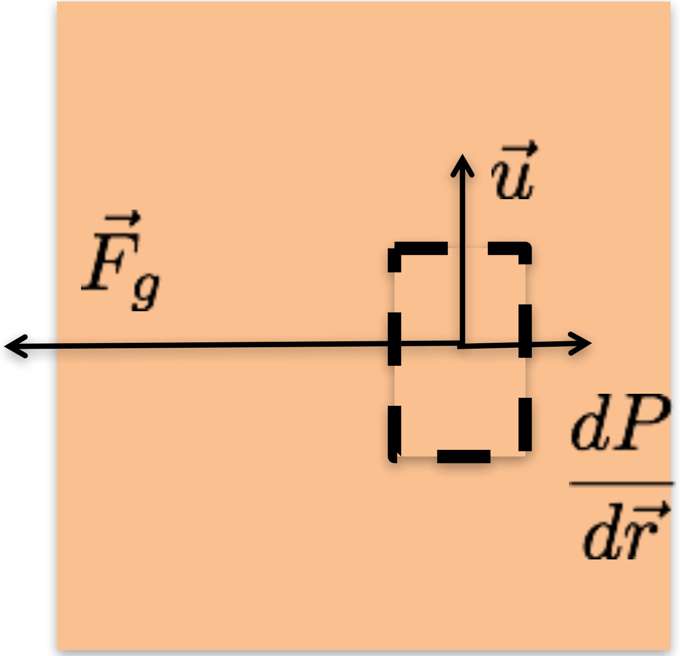
A. Zsom, C.W. Ormel, C. Guettler, J. Blum, C.P. Dullemond

Radial drift

A body only under the acceleration of gravity moves at a Keplerian rate about the Sun



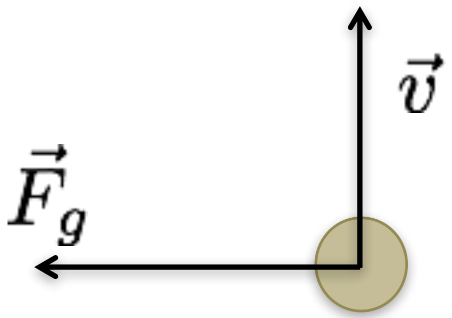
A disk of gas is also pressure supported so it needs a stronger gravitational pull to orbit at the same speed

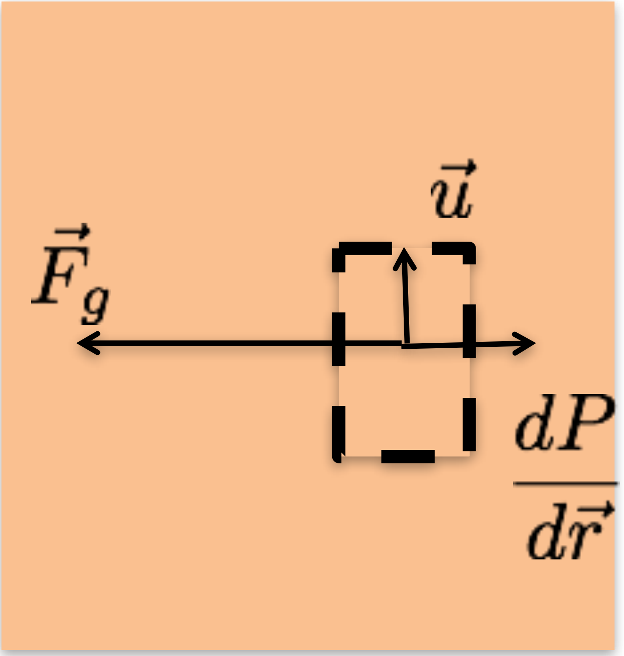


Radial drift

If a body and a parcel of gas are at the same distance from the Sun, then their gravitational accelerations will be the same so they will orbit at different speeds

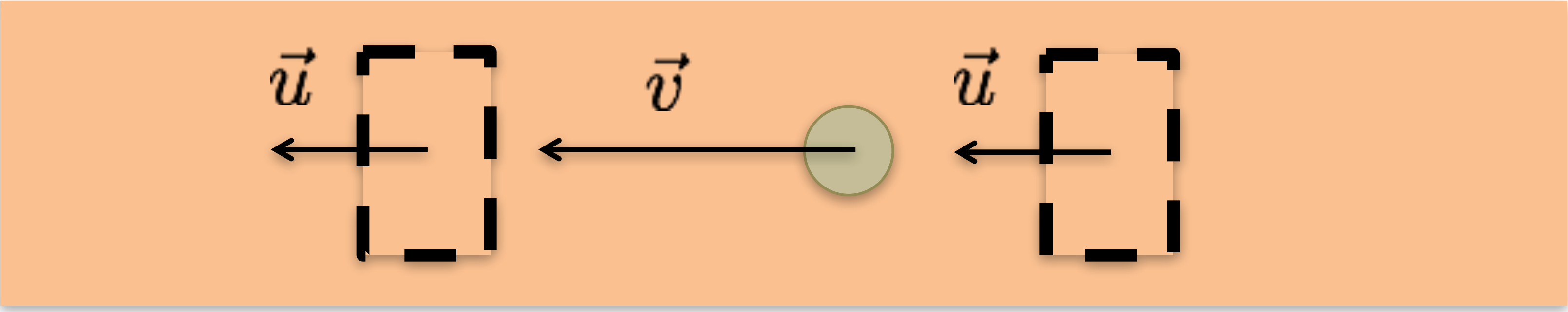
Note: they both will be on the same circular orbit despite this difference in speeds



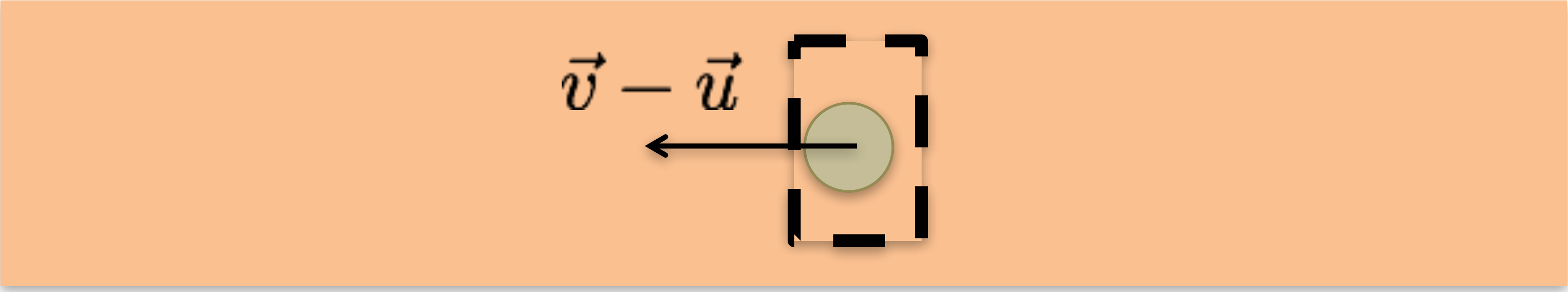


Radial drift

The body is catching up and passing the gas



This is often shown as a relative velocity



Radial drift

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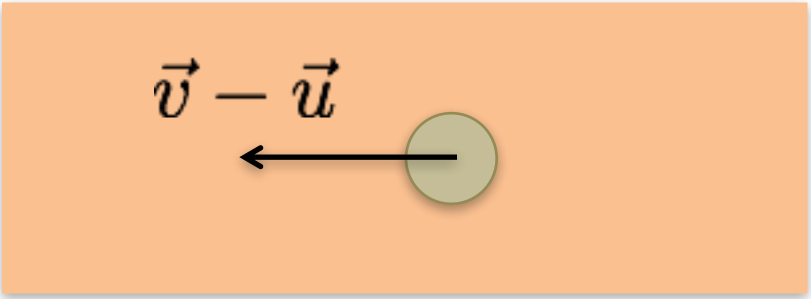
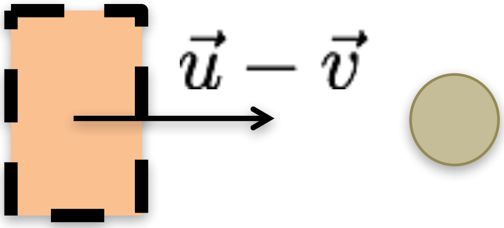


Either in the gas frame



Or in the body frame

So gas flows past the body creating a headwind

Like on a bicycle a headwind saps energy from the body

Radial drift

Bound orbits have negative energy

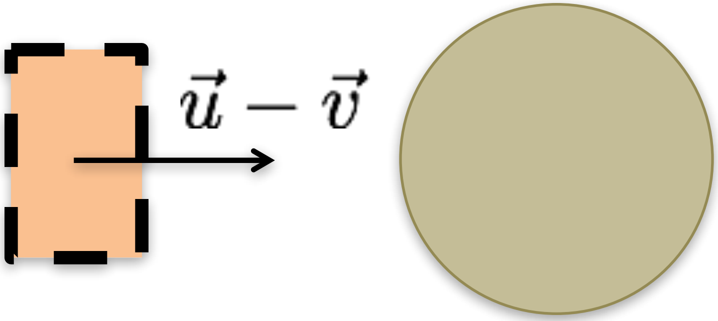
More tightly bound, i.e. small semi-major axis, orbits have less energy, i.e. more negative,

SO

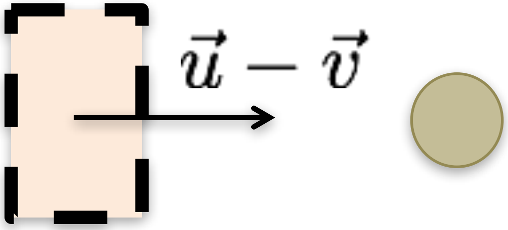
Losing energy to a headwind shrinks the orbit

Radial drift

Larger objects interact more weakly with the gas



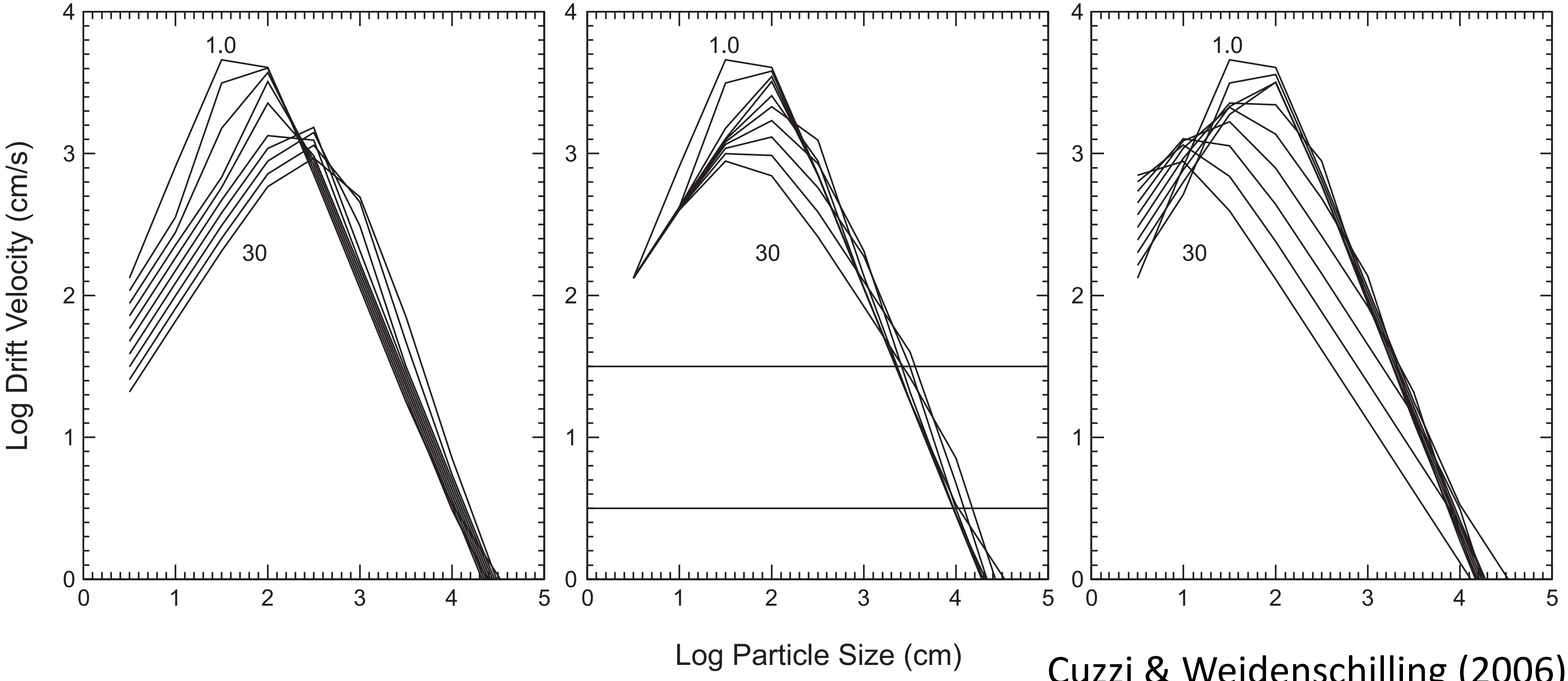
Less dense gas interacts more weakly with the body



Radial drift

1 cm through 10 m particles drift faster than the gas

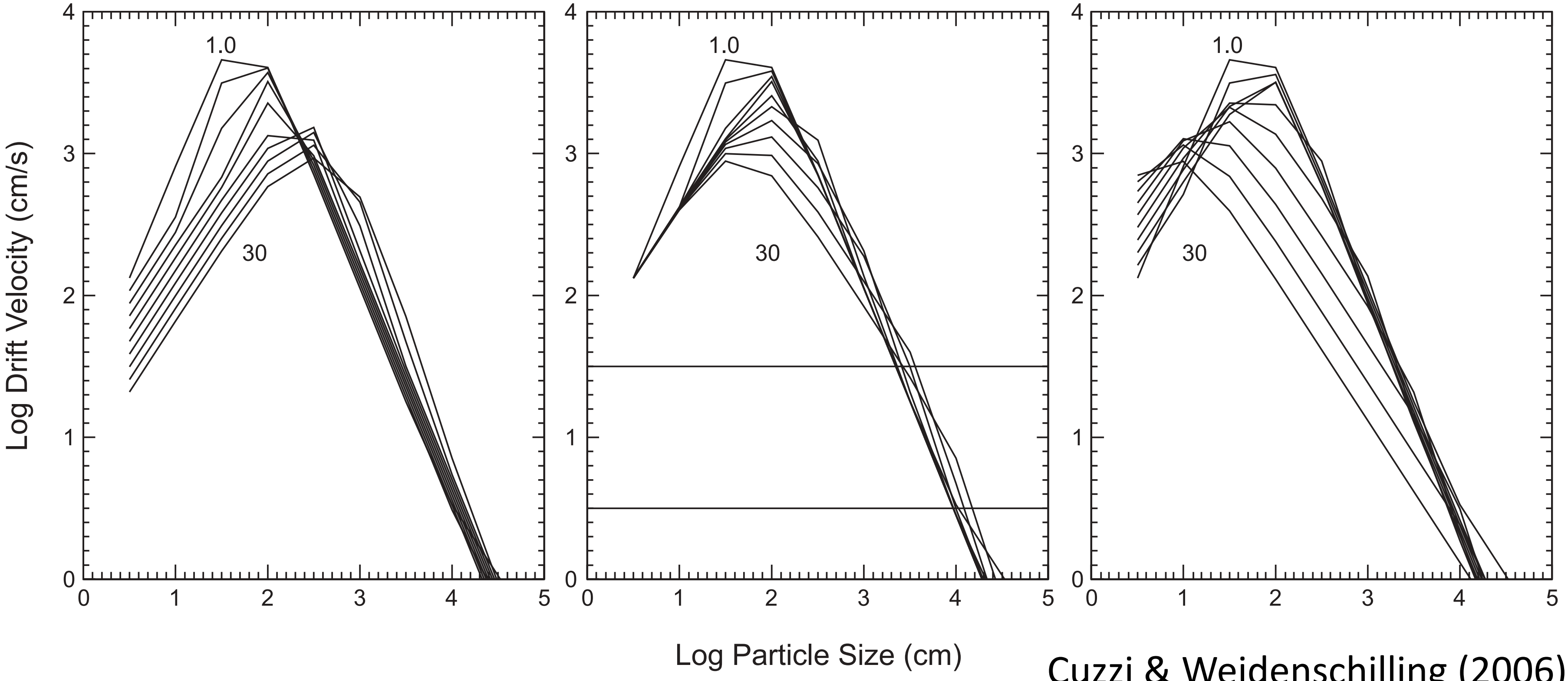
Only bodies larger than 10 km drift slower than the age of the nebular disk



Cuzzi & Weidenschilling (2006)

Radial drift

When the body is so well-coupled to the gas, the body no longer experiences a true headwind but is carried with the gas as it is advected inward



Cuzzi & Weidenschilling (2006)

Problems with pairwise growth

- It assumes collisions are accretionary when they could be bouncy or fragmentary

- It’s too slow compared to radial drift

Planet formation needs an alternative

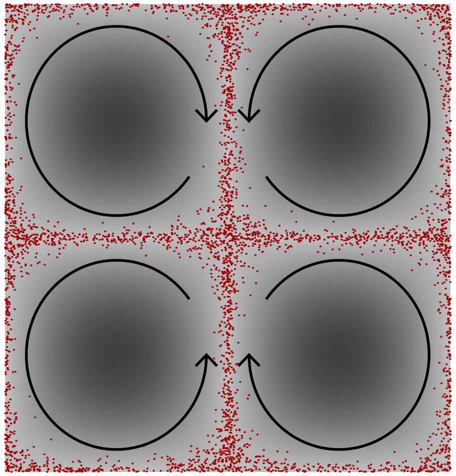
Can more than two objects be brought together at once?

Gravitational instabilities

Because asteroids were born big and there are many barriers between ~<m and >100 km asteroids, it would be advantageous to go suddenly from one regime to another

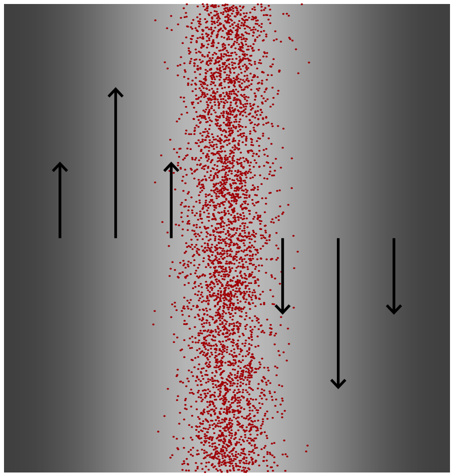
1. Classical
2. Aero-assisted, gravoturbulent, gas necessary
    1. Turbulent concentration
    2. Pressure bumps
    3. Streaming instability

Eddies



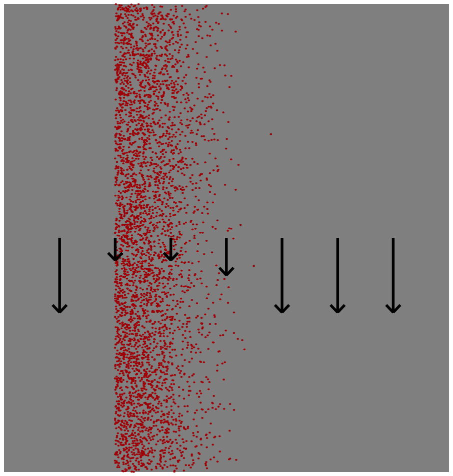
$l \sim \eta \sim 1$ km, St $\sim 10^{-5}$–10^{-4}

Pressure bumps / vortices



$l \sim 1$–$10\ H$, St ~ 0.1–10

Streaming instabilities



$l \sim 0.1\ H$, St ~ 0.01–1

Classical gravitational instability

This field starts with some of the greats in planetary science: Kuiper, Urey, Chandrasehkar

Mass sediments onto a very thin mid-plane layer

This disk undergoes gravitational instabilities to create 100 m size bodies

These bodies undergo further instabilites to create the planets and asteroids

Goldreich & Ward 1973

Classical gravitational instability

The primary challenge of this model is the sedimenting of the dust to a thin mid-plane layer

Goldreich & Ward (1973) assumed a particle scale height of less than 3 x 10^{-5}

Modern models (e.g. Youdin & Lithwick, 2007) predict that even in dead zones the particle scale height for sedimented grains is about 3 x 10^{-4} due to turbulent diffusion

Goldreich & Ward 1973

Turbulent Concentrations

Eddys and vortices create regions of pressure highs and lows

These attract and repel particles

The requirements for these turbulent concentrations to become large enough to become gravitationally unstable are likely never met

Pressure bumps

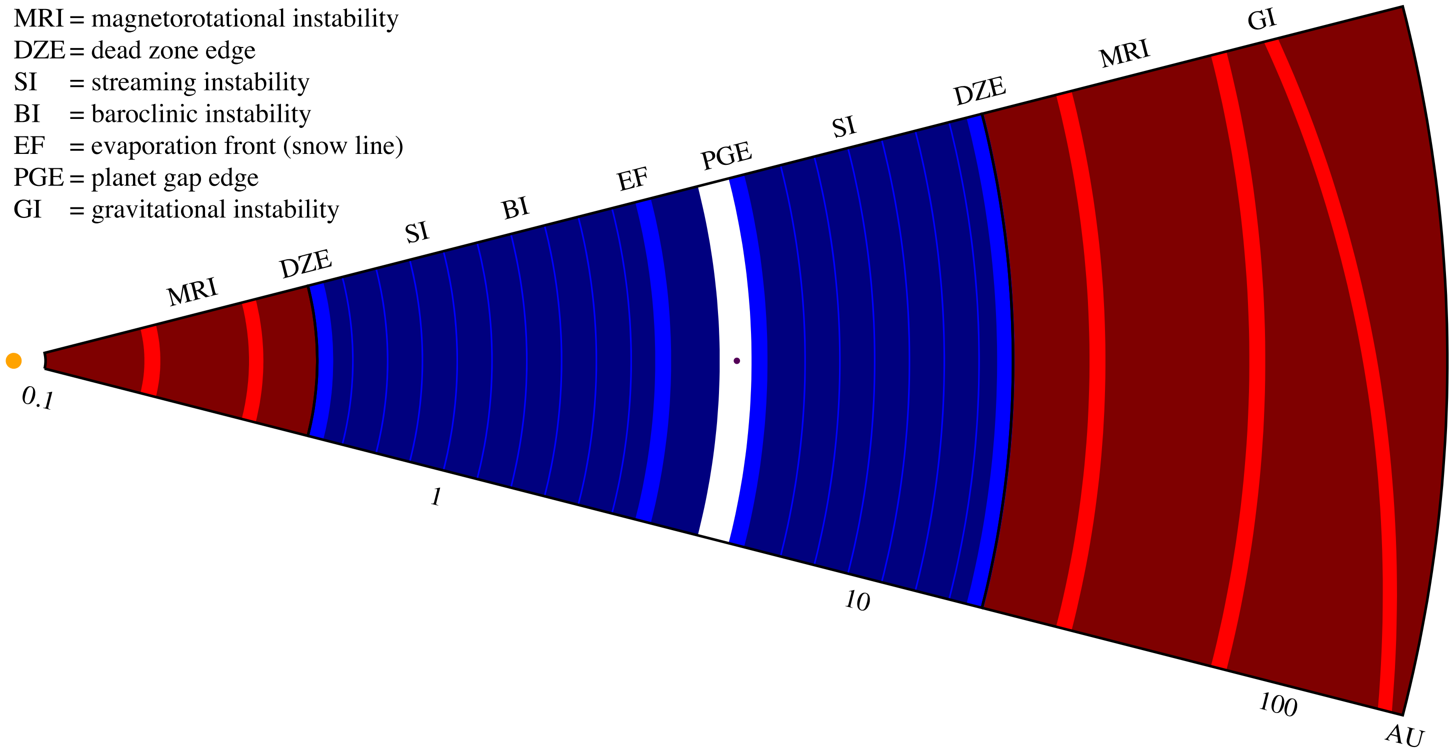
Typically, because the inner disk is hotter, the pressure gradient is directed outward

If the temperature gradient is inverted due to an opacity transition, then the pressure gradient can be directed in the other direction

Furthermore, gravitational perturbations on the disk such as giant planets can create “pressure bumps”

Back to pressure bumps

Pressure bumps are unlikely to concentrate particles enough on their own but they create places where other processes can be more efficient

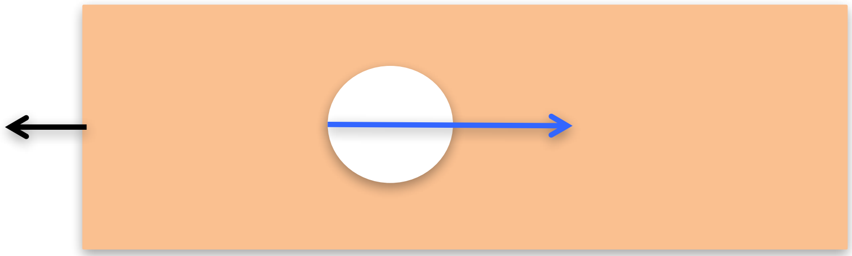


MRI = magnetorotational instability
DZE = dead zone edge
SI = streaming instability
BI = baroclinic instability
EF = evaporation front (snow line)
PGE = planet gap edge
GI = gravitational instability

Johansen et al. (2014)

Streaming instability

Aerodynamic gas drag slows the motion of an object in orbit about the Sun



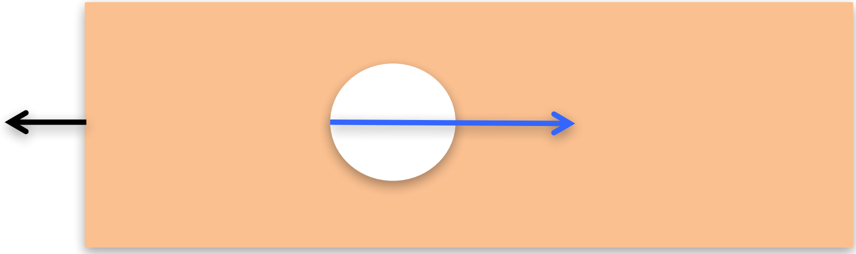
Newton's third law tells us that there is a back reaction on the gas accelerating its motion

Remember that the size of the drag term on the body is proportional to the difference in velocity between the gas and the body

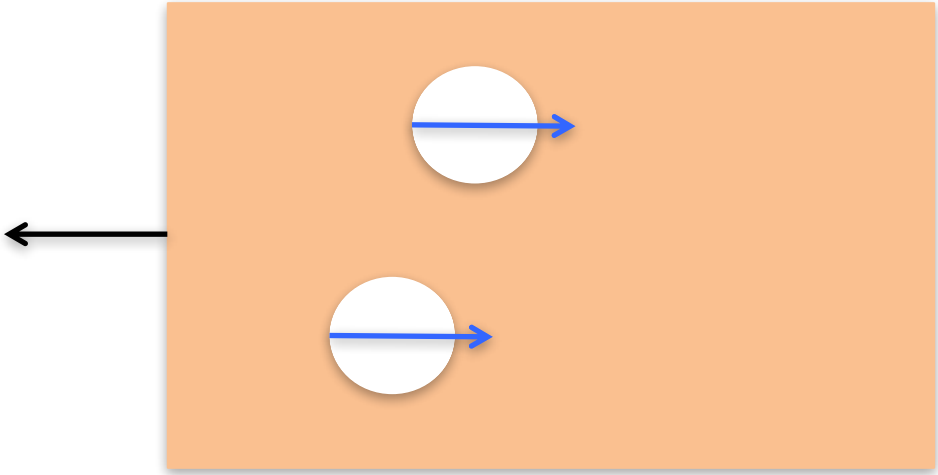
Streaming instability

Pushing gas is difficult!

Irregular shaped objects, gas self-interaction, etc.



But the effectiveness of pushing gas increases with the number of bodies pushing



As the feedback on the gas increases, the velocity difference between the gas and bodies decreases, so the drag decreases

Streaming instability in a bicycle race

The peloton is used by racers to reduce energy expenditures

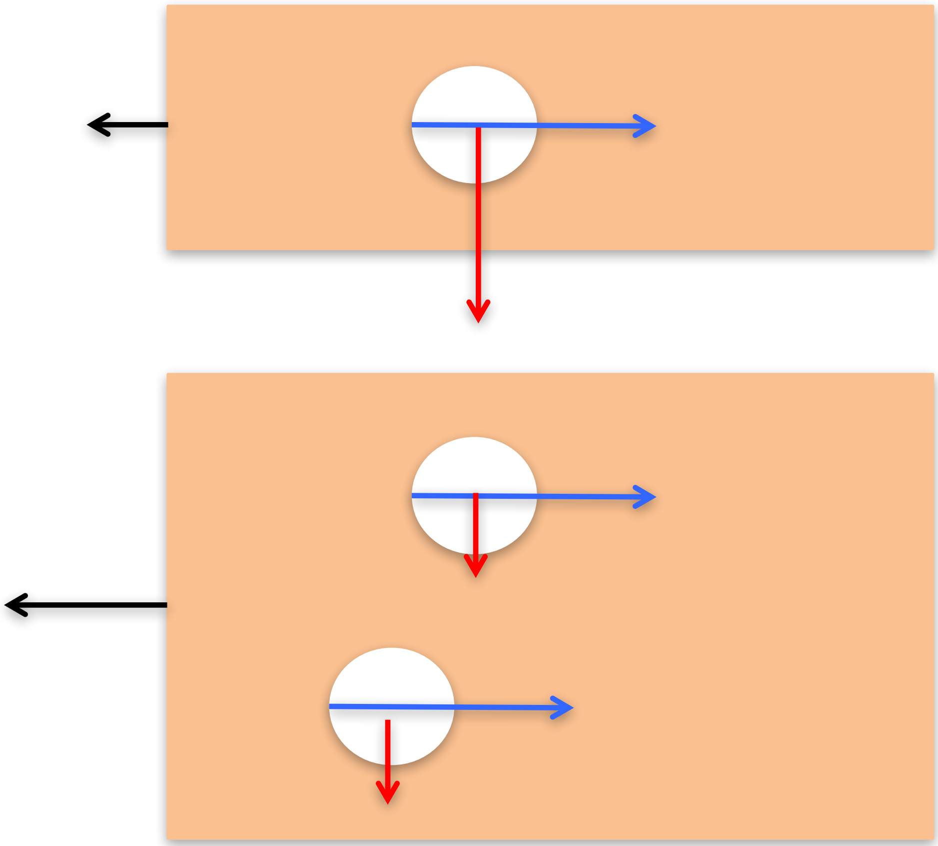
Following bicyclists enter the slipstreams of bicyclists in front of them and experience drag reduction

Streaming instability

As the difference between the solid and gas velocities decrease the radial drift decreases

This means that outer bodies catch up with inner bodies

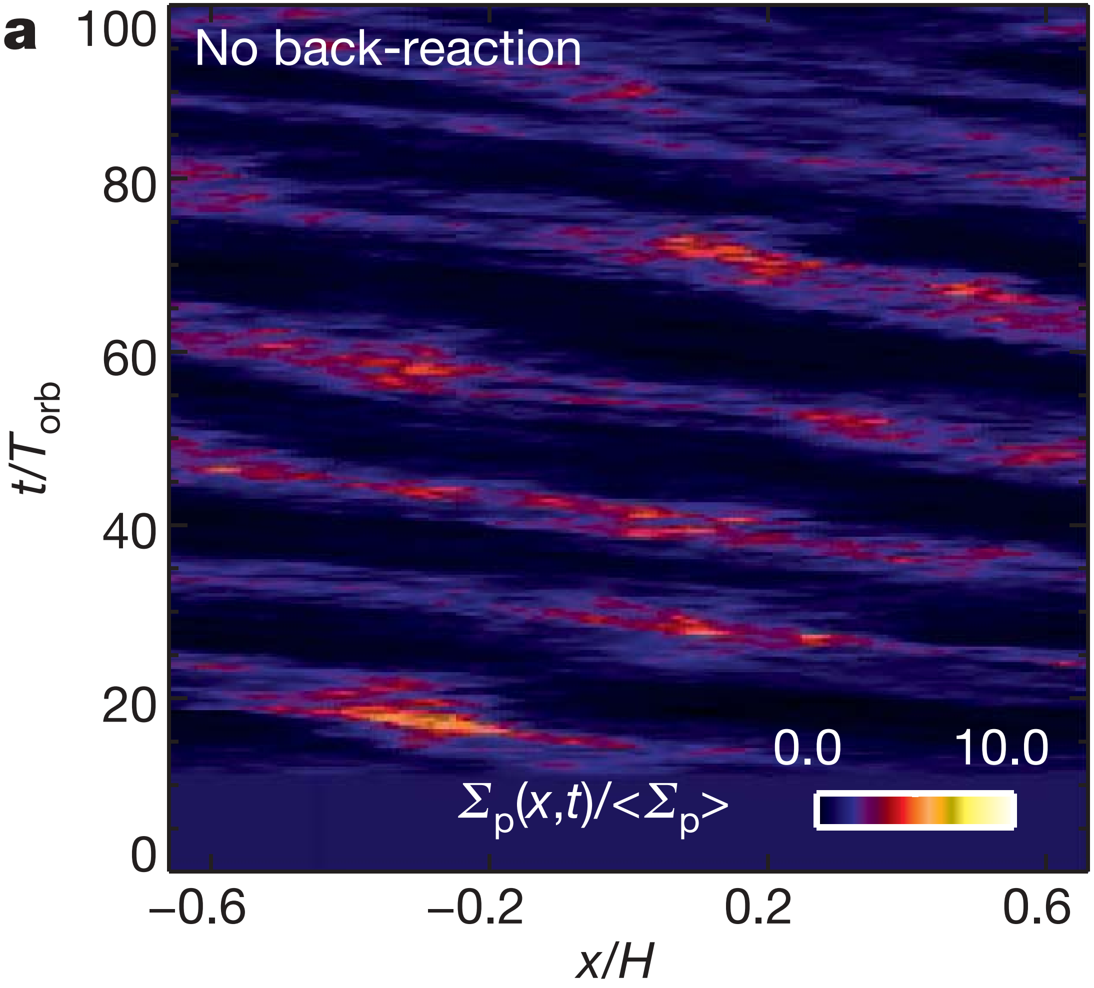
As the number increases, the velocity difference decreases, more particles catch up, and so on. It's a runaway effect.



Streaming Instability in a disk

Radial drift to aerodynamic gas drag seen as a drift in mean anomaly

Clumps are due to turbulent eddy effects

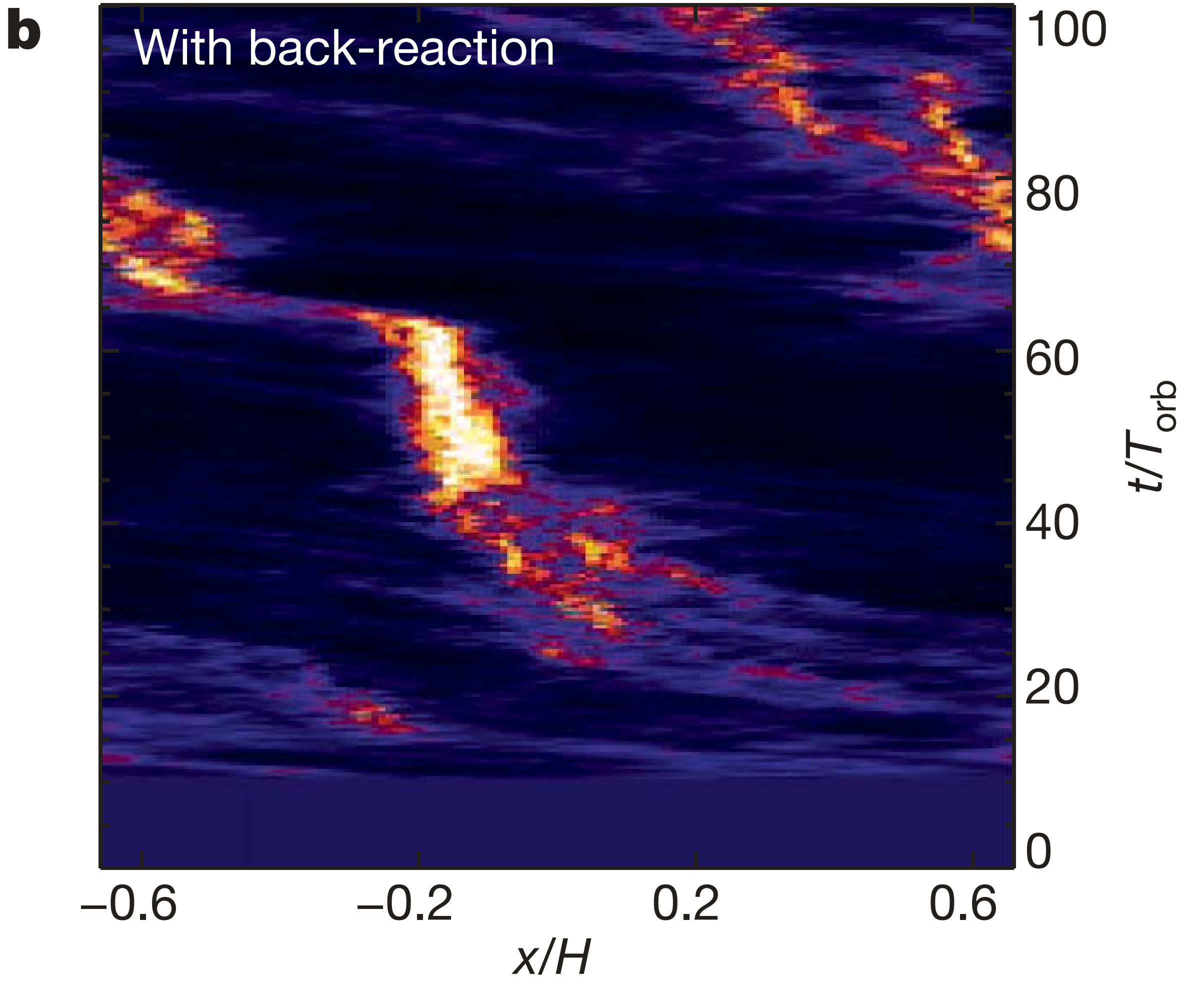


Johansen et al. (2007)

Streaming Instability in a disk

Clumps are much larger

Radial drift can be halted by the back-reaction

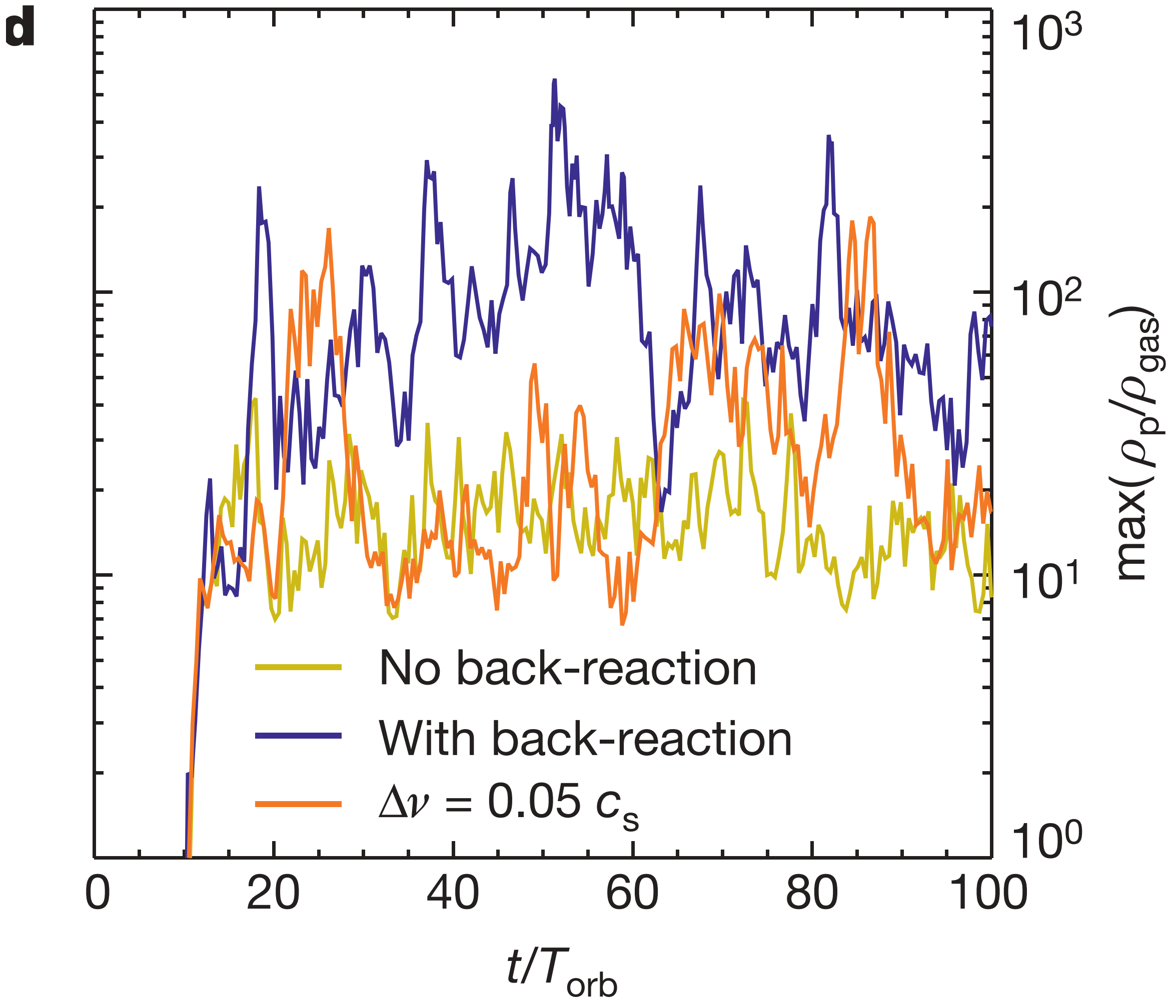


Johansen et al. (2007)

Streaming Instability in a disk

Clumps of particles get quite massive when back-reaction is considered

Peaks with over 100 times gas density as opposed to about 10 before



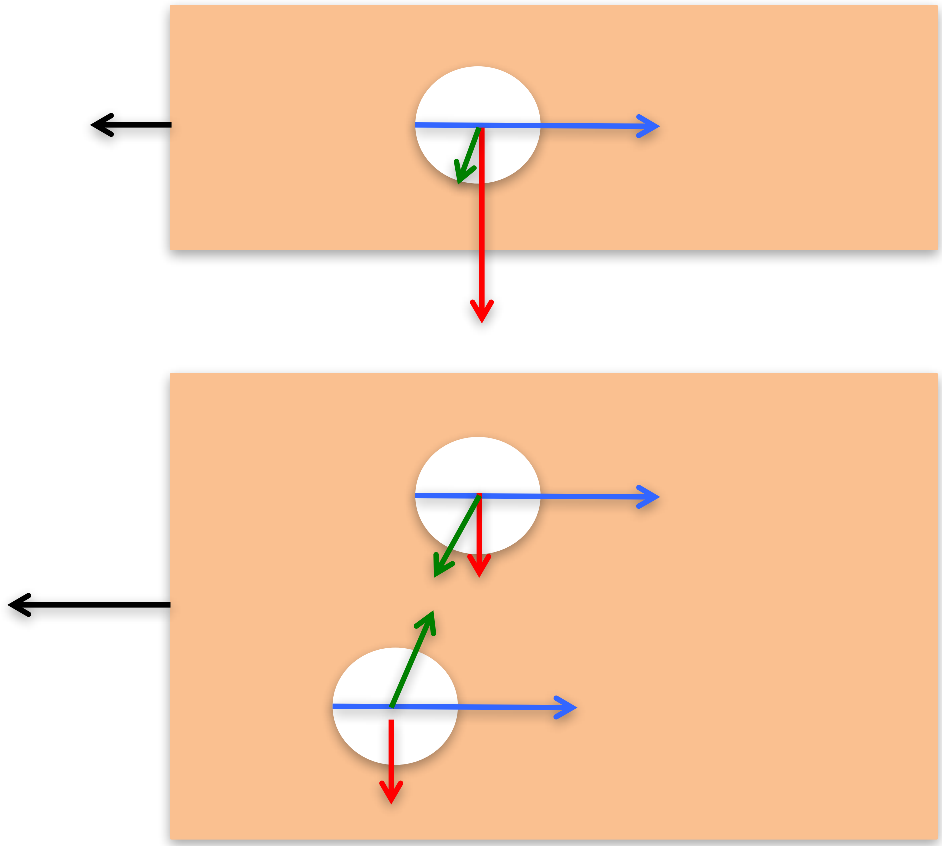
Johansen et al. (2007)

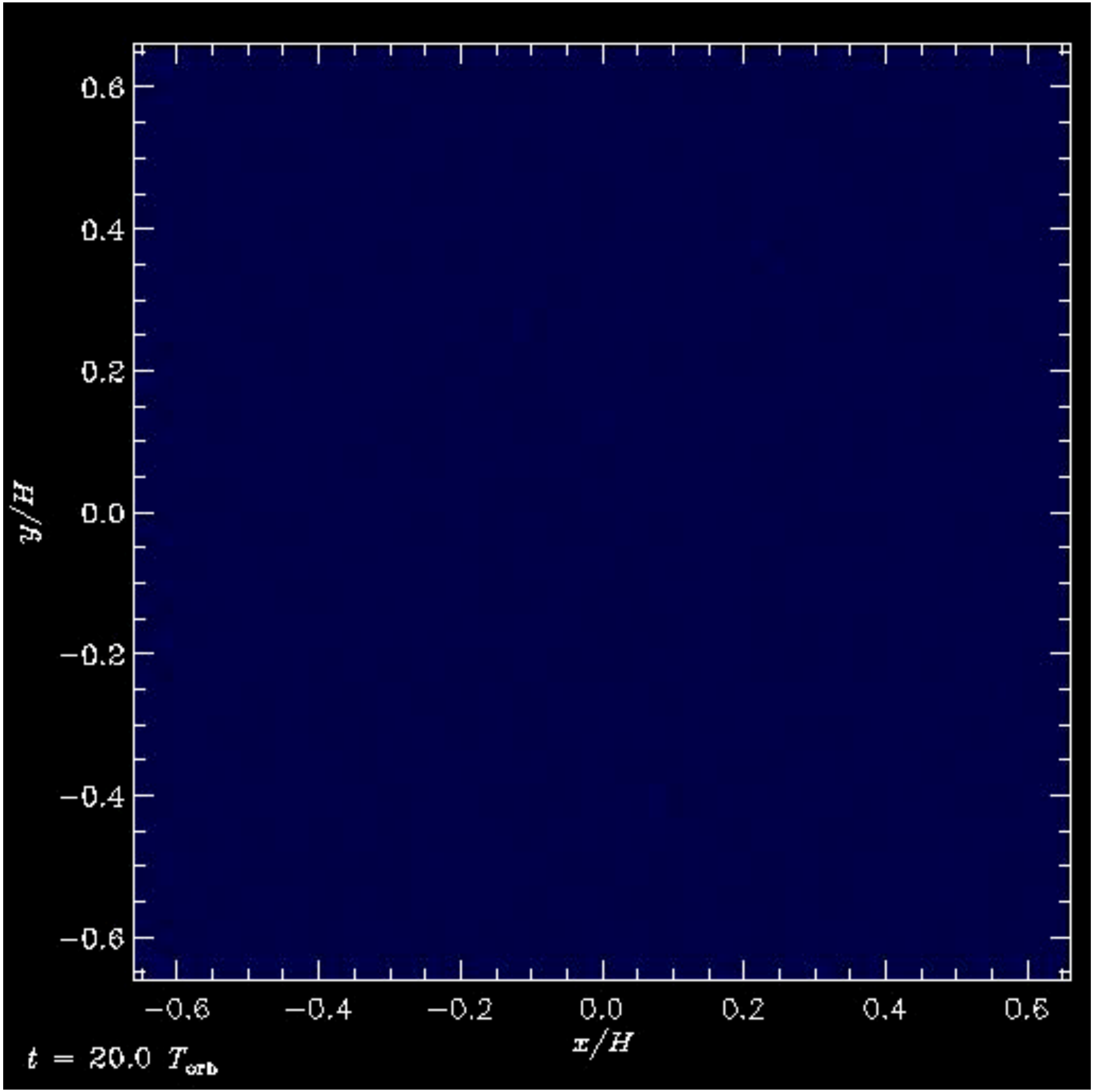
Streaming instability in a cartoon

Add a further process the gravity between bodies

Very akin to the Jean’s mass for gravitational collapse into Stars

The bodies must reach an appropriate overdensity criterion before they collapse into a single body





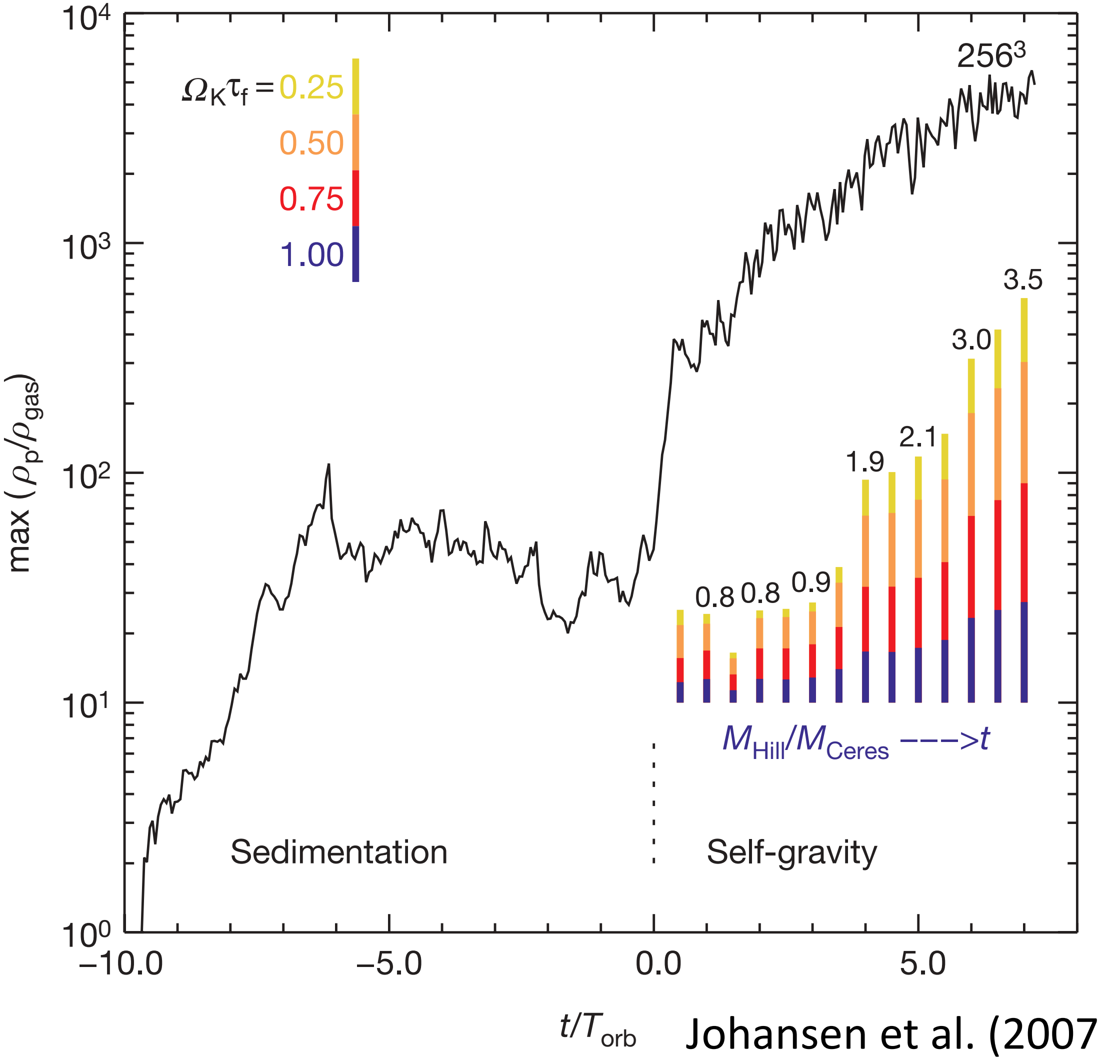
Johansen et al. (2007)

Streaming Instability in a disk

With self-gravity the clumps can reach nearly 10,000 times the gas density

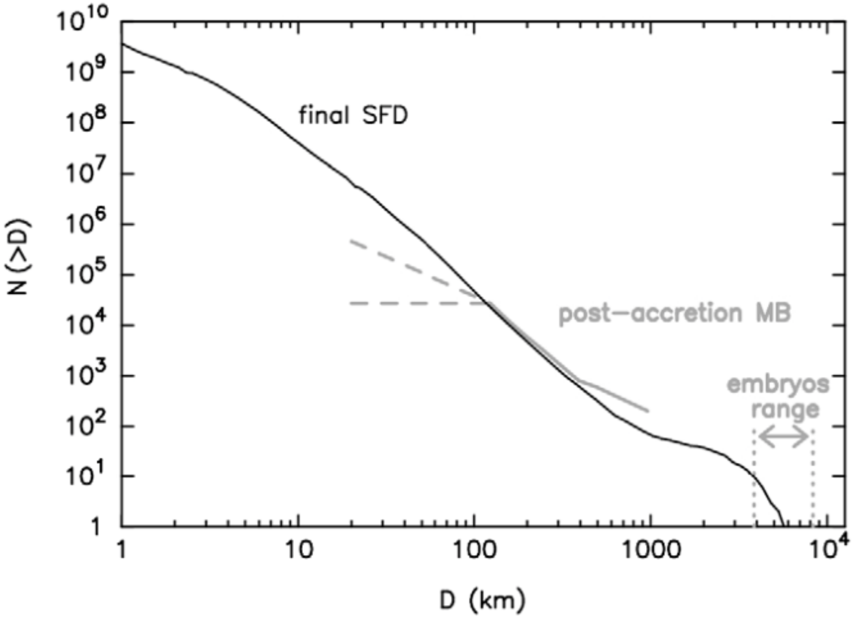
Collapse times are short

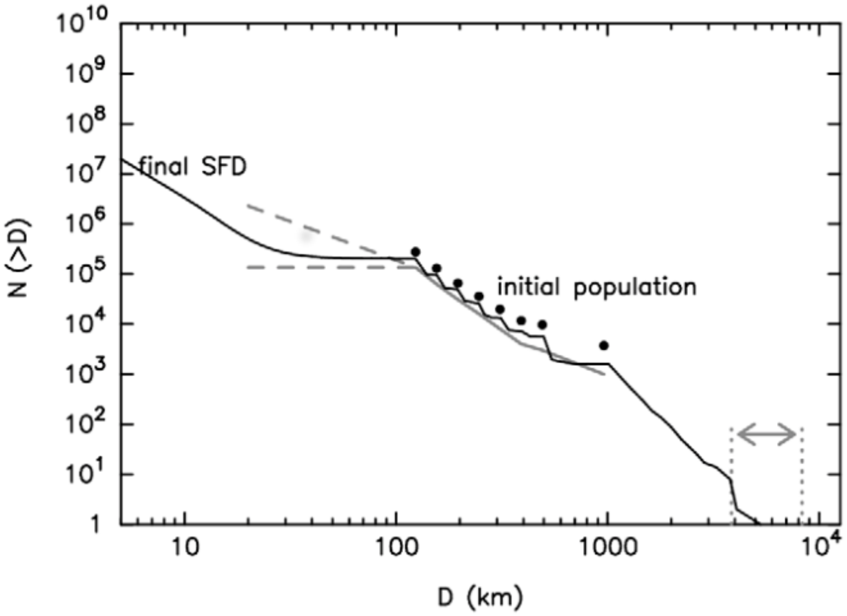
Final bodies are more massive than Ceres



Johansen et al. (2007)

Successes of the streaming instability



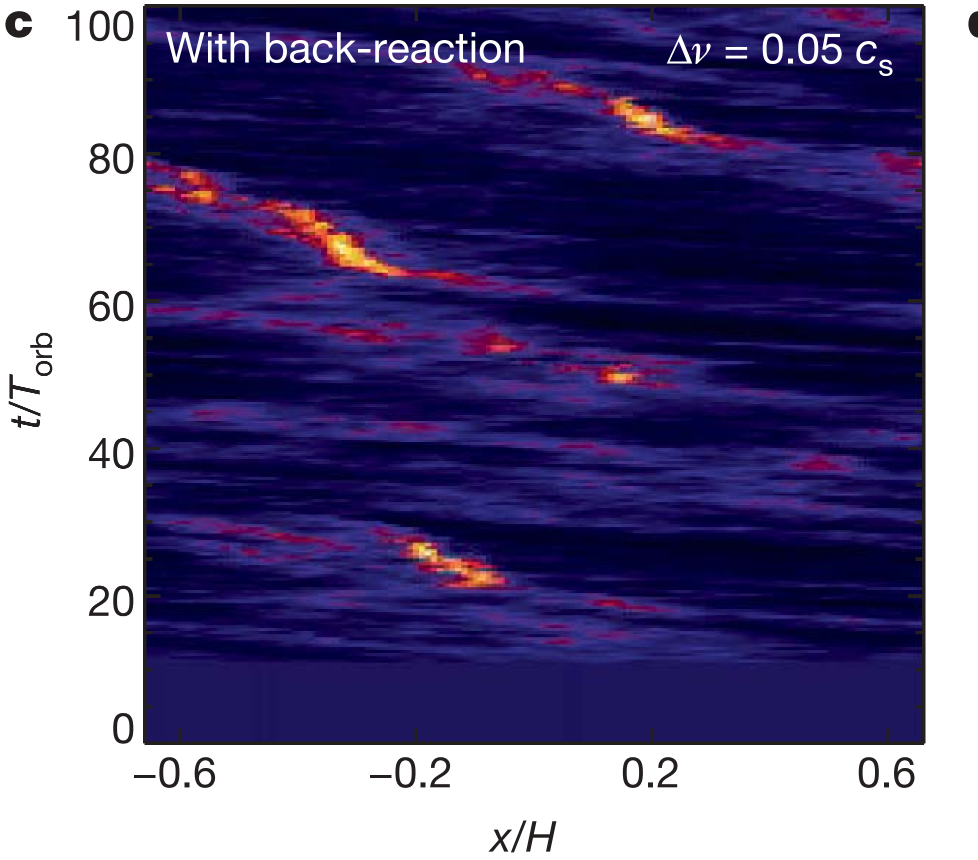


It creates the large asteroids, that are thought to be leftover planetesimals

And it does so directly from small bodies

Caveats to the streaming instability

- Unlike pairwise accretion, it is inefficient for small grains
- It is most efficient for grains that are very close or at the various size barriers
- Works better with higher dust to gas ratios
- Works better with low levels of turbulence and within pressure bumps



Step 1 Complete!
Pebbles to Planetesimals

Take-away messages from the first section

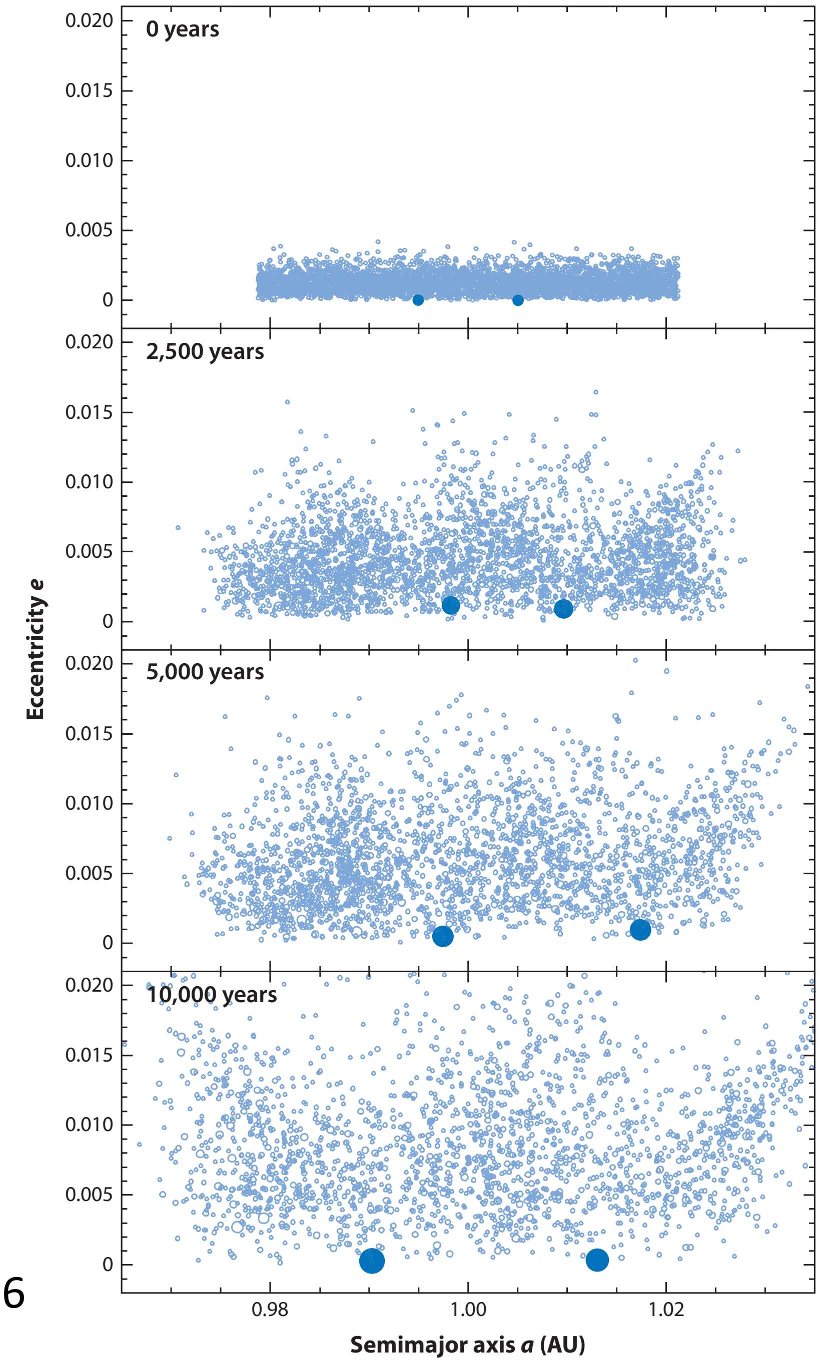
Radial drift is an incredibly important aerodynamic effect in nebular disks and particles are attracted to gas pressure highs

The streaming instability works like a peloton in a bike race, particles catch up with one another until there is enough density for the structure to gravitationally collapse

Runaway growth

This phase occurs when

- Most of the mass is in the small bodies
- The relative velocities are close to the escape velocities

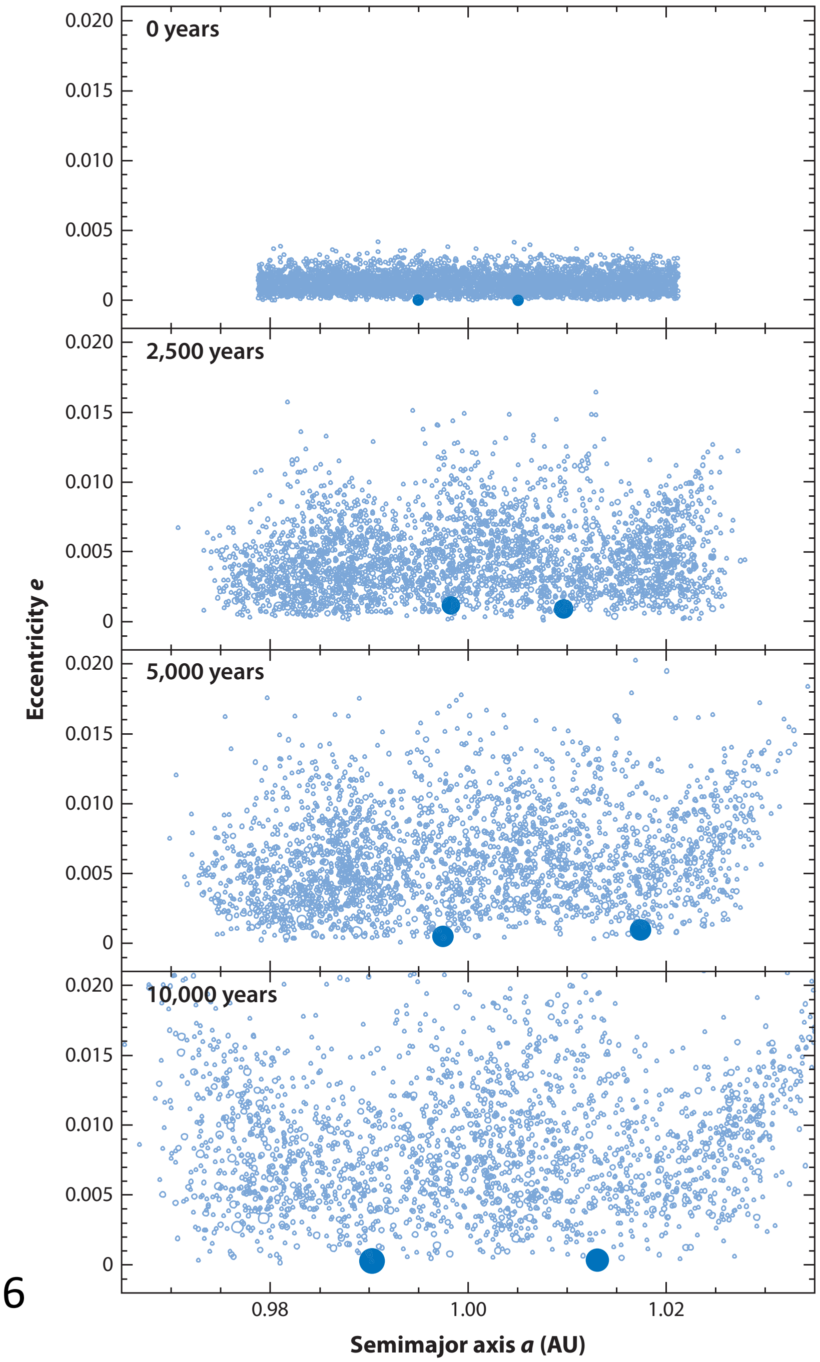


Kokubo & Ida, 1996

Runaway growth

The gravitational focusing factor enhances the cross-section of the largest bodies more than the others

They grow significantly faster and “runaway” from the rest of the population

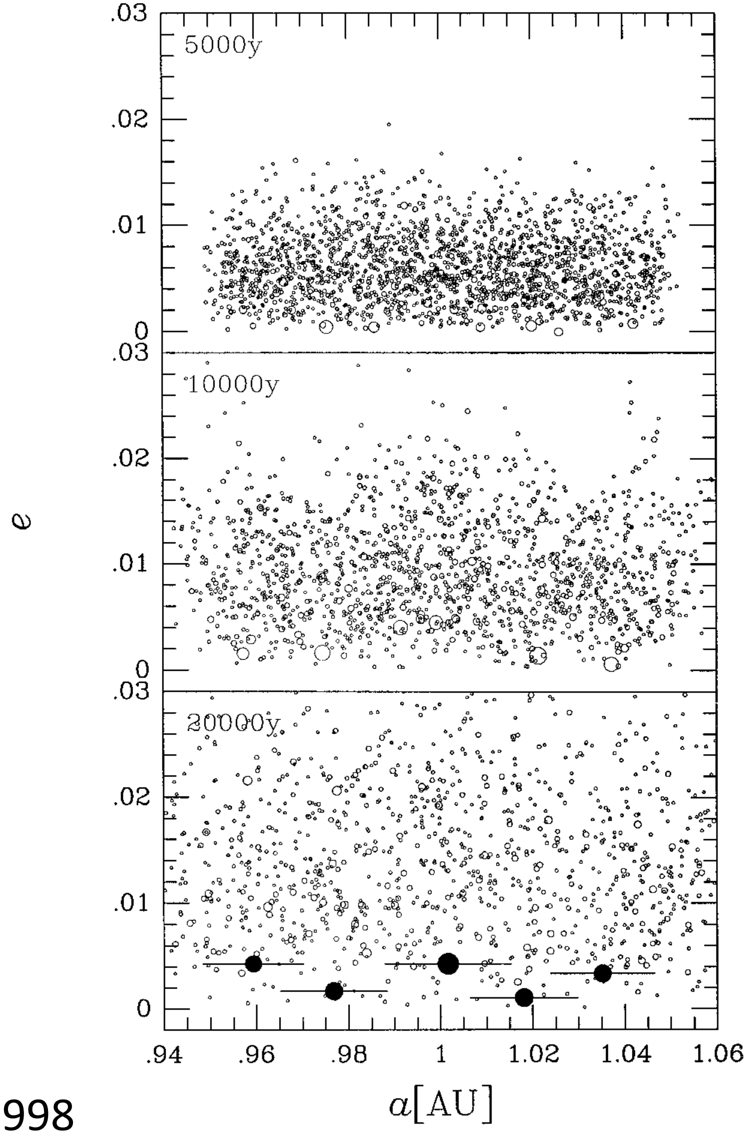


Kokubo & Ida, 1996

Oligarch growth

As the largest embryos grow, they excite the smaller planetesimals

Once the planetesimals have relative velocities much larger than the escape velocity of the largest bodies, runaway growth ends

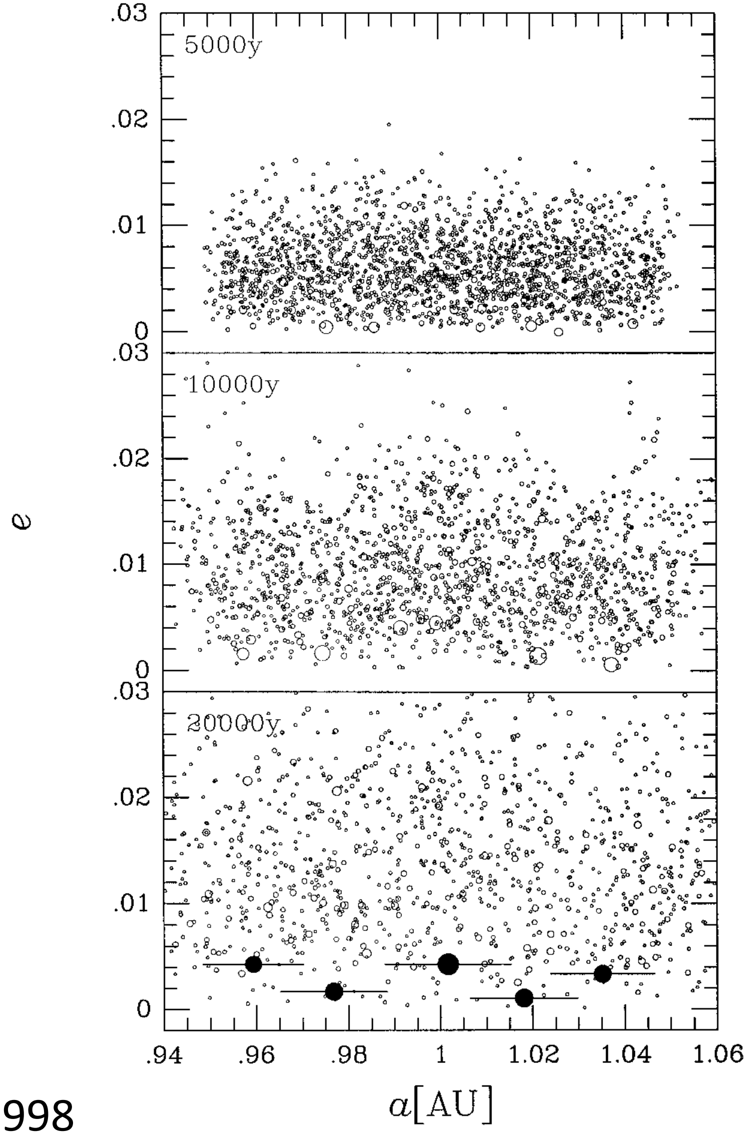


Kokubo & Ida, 1998

Oligarch growth

New steady state is established:

- Oligarchs are all about the same mass
- They have low eccentricity and inclination orbits
- They are about 10 mutual hill radii apart



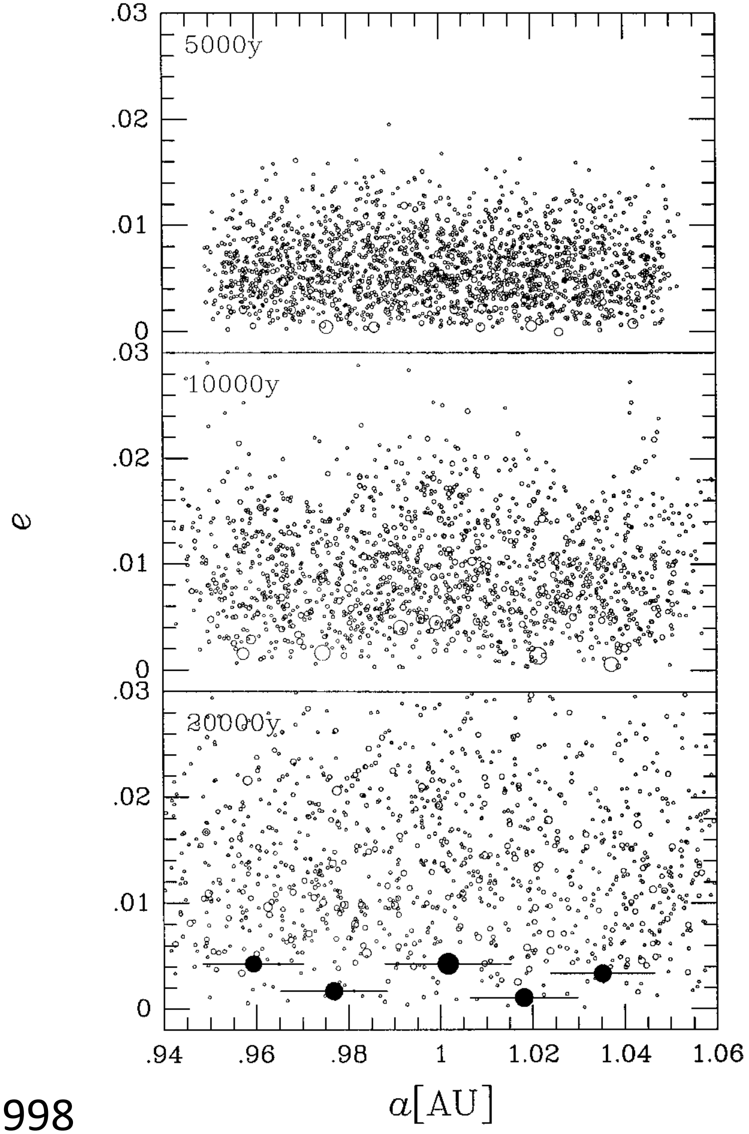
Kokubo & Ida, 1998

Oligarch growth

This lasts until a de-stabilizing event occurs:

- Removal of the gas
- Removal of the planetesimals
- Gravitational perturbation

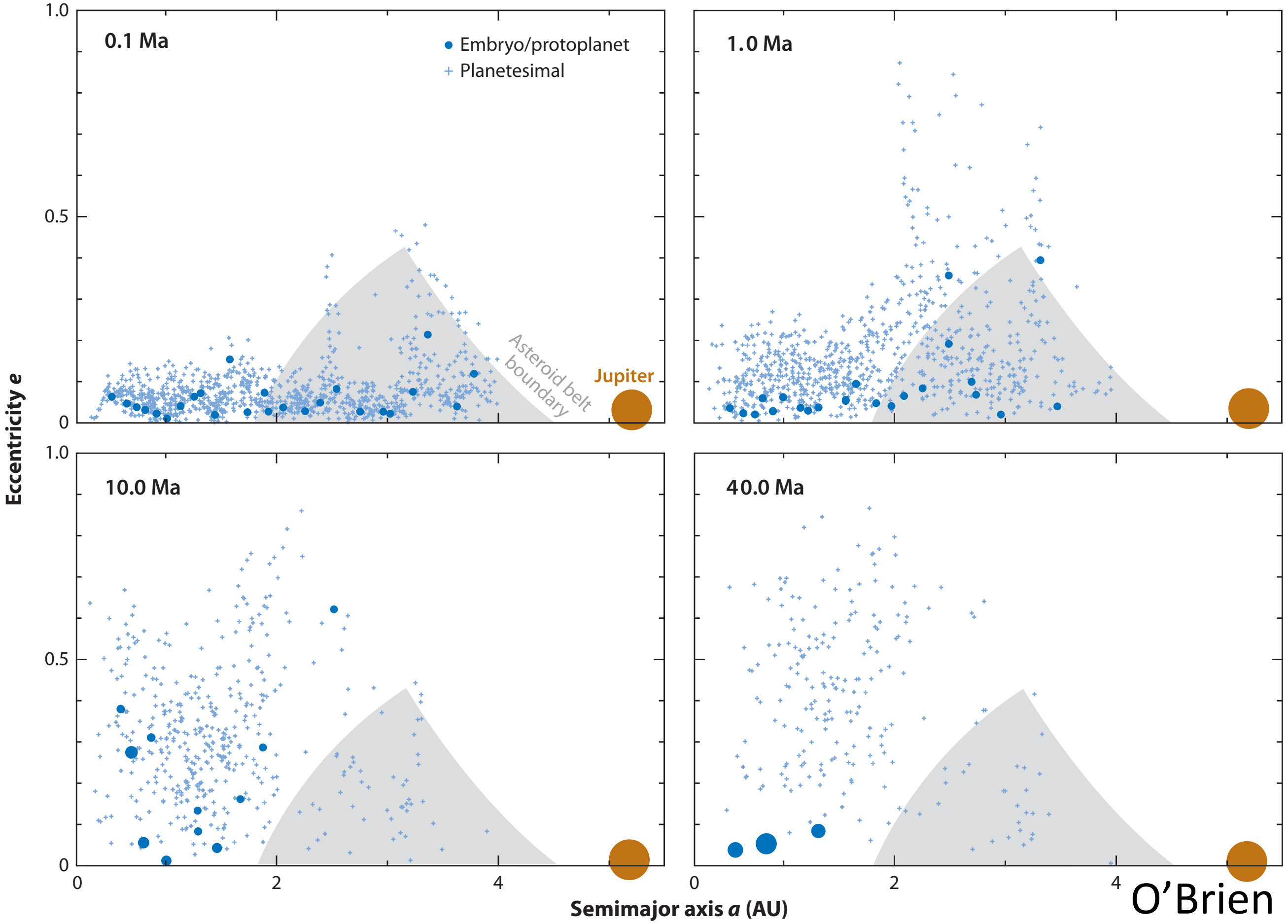
Once de-stabilized, they obtain crossing orbits and impact



Kokubo & Ida, 1998

Runaway and oligarchic growth successes

- Reproduces the terrestrial planets well

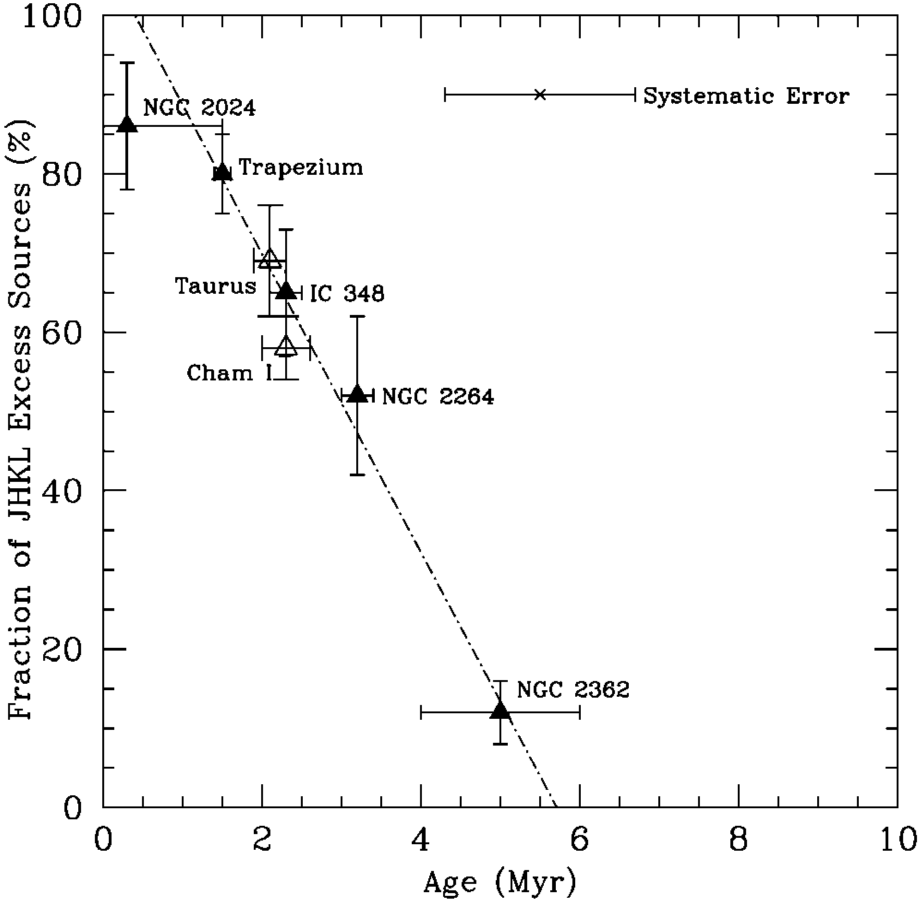


O'Brien et al. (2006)

Runaway and oligarchic growth challenges

Formation of 10 Earth mass core of Jupiter can take billions of years …

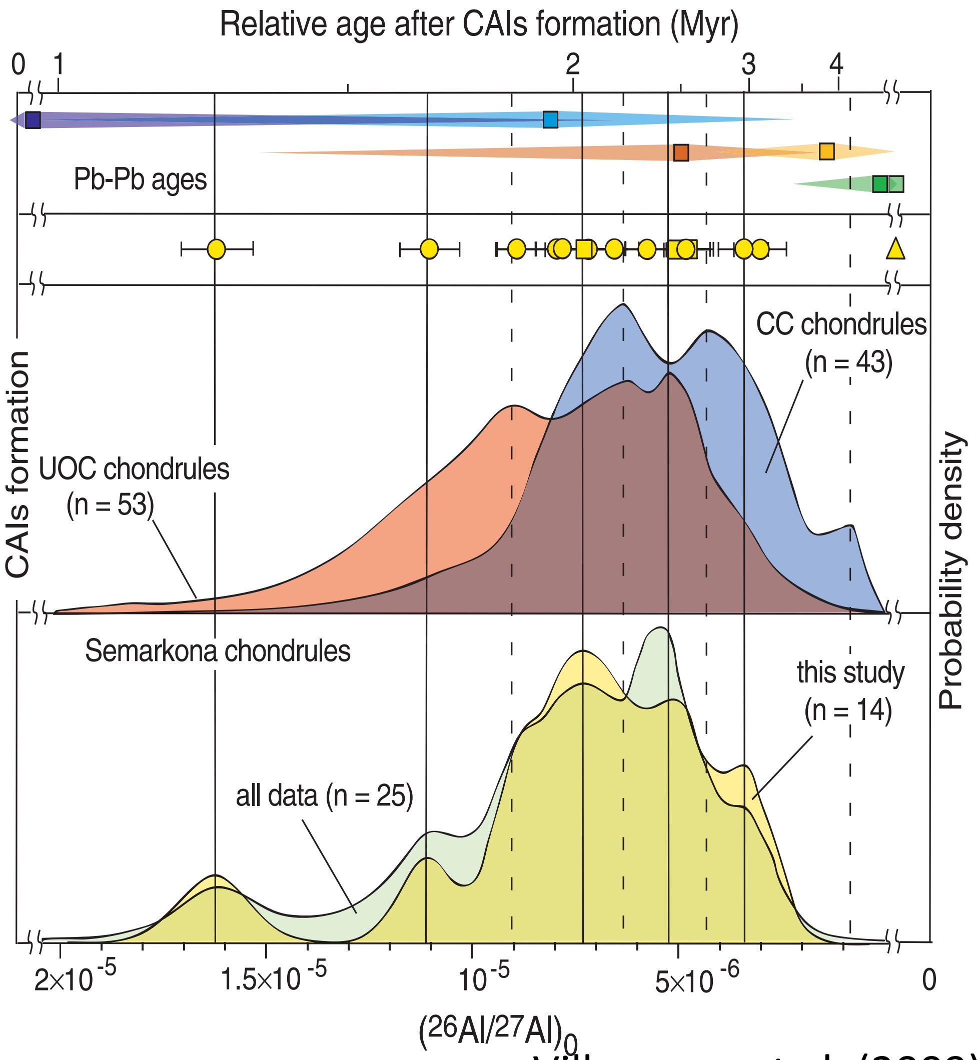
But we know that disks likely lasted only a few million years



Haisch et al. (2001)

Chondrules also contradict such slow growth

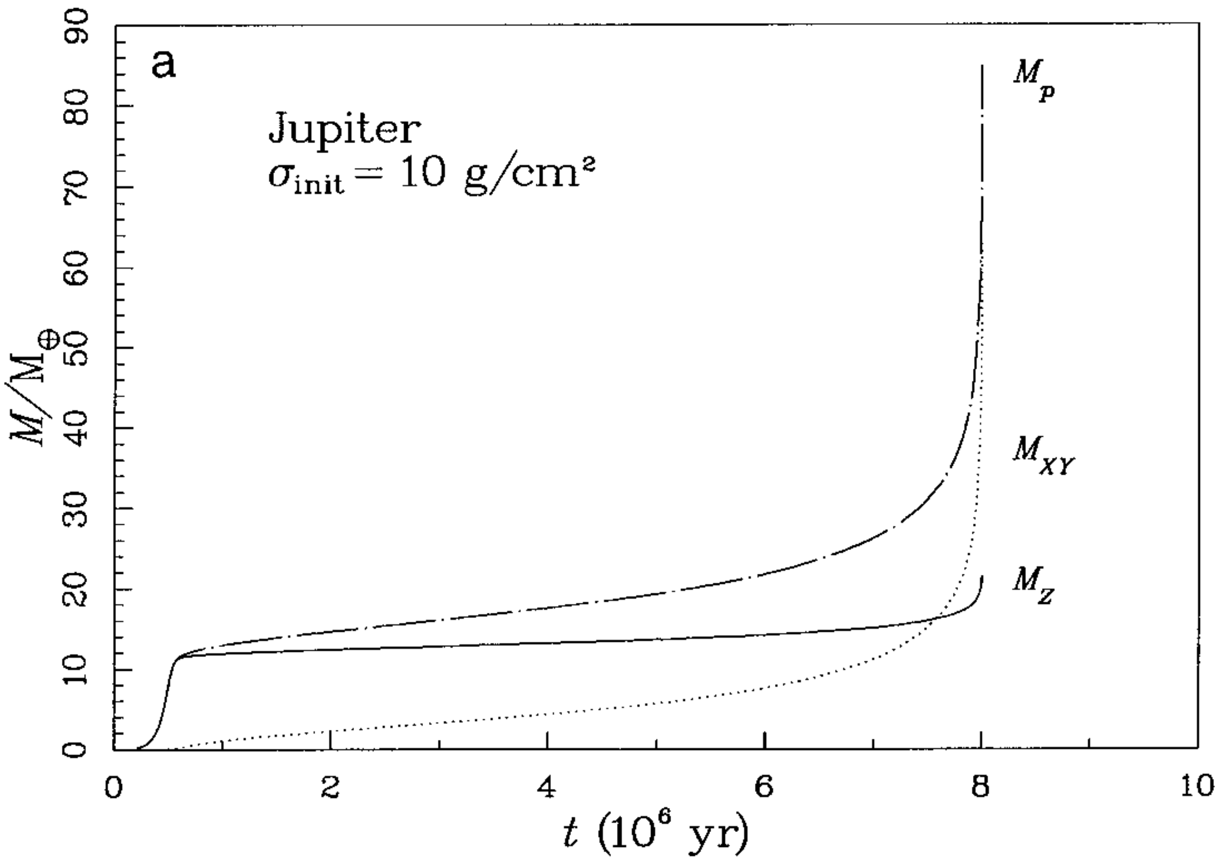
Chondrules come from the first 3 million years of Solar System history



Villeneuve et al. (2009)

Core accretion model for the formation of the giant planets

If a ~10 Earth mass core exists early in the nebular disk, then it can grow to a gas giant mass within the lifetime of the disk



Pollack et al. (1996)

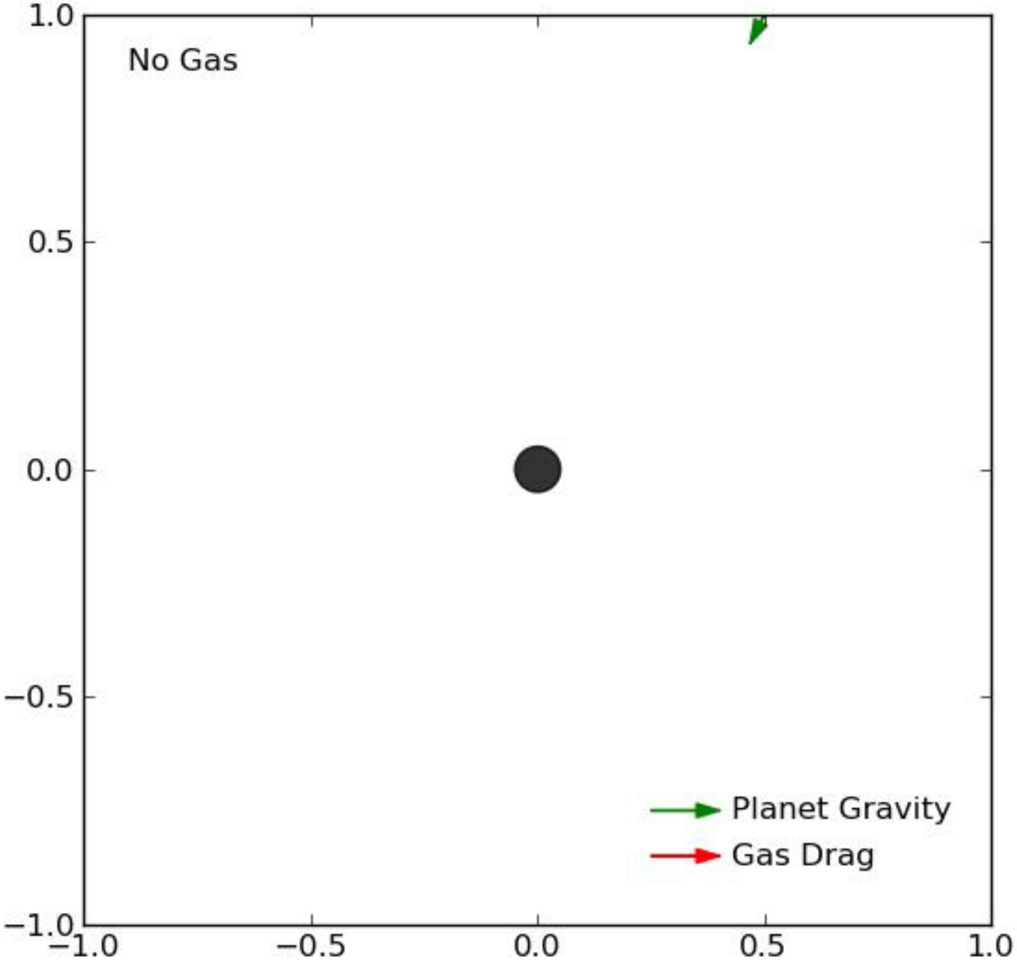
The challenge

Build a 10 Earth mass core that ends up near Jupiter’s orbit in ~3 Myr

There have been a number of attempts

1. Direct gravitational collapse
2. Assembly elsewhere and migration

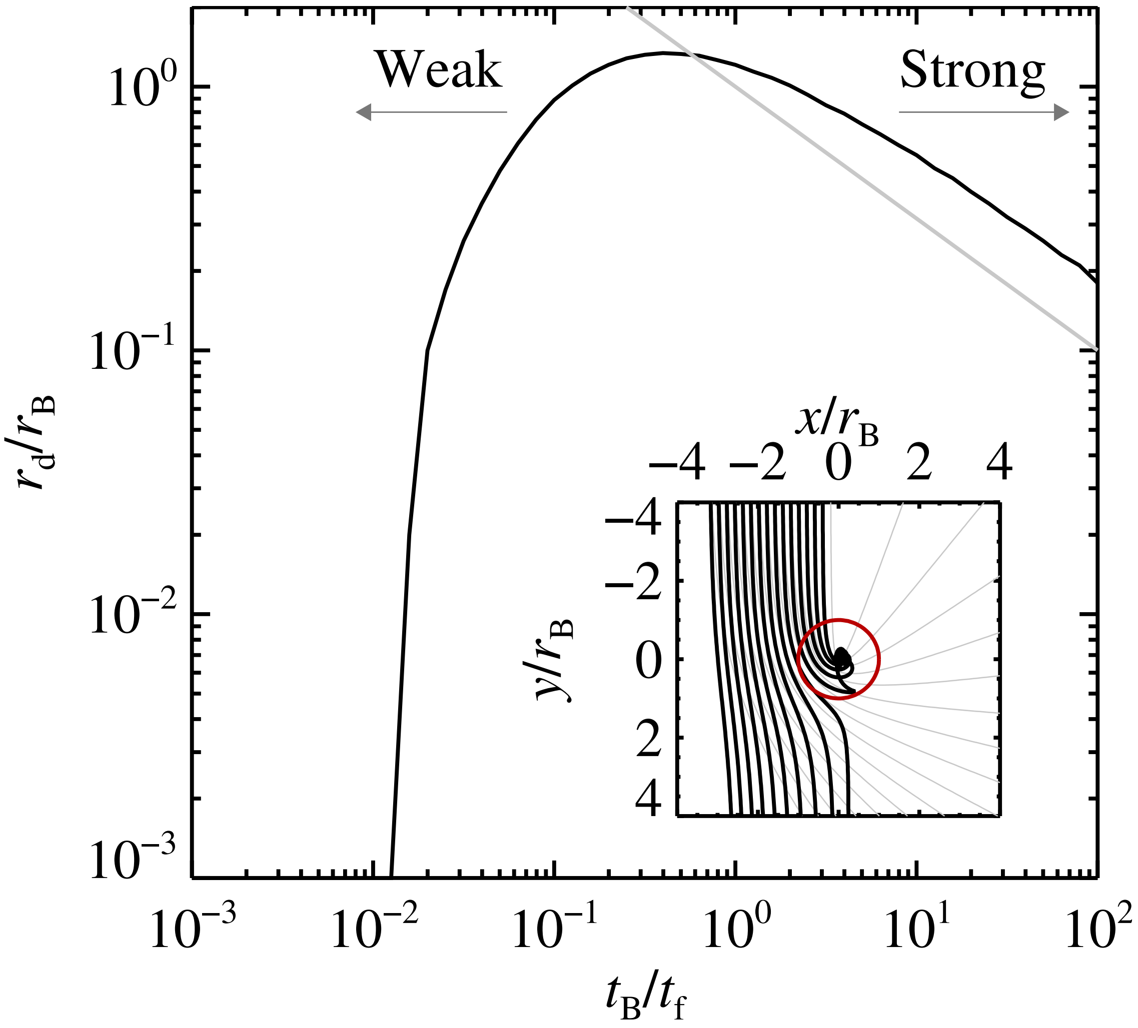
Effect of gas drag on pebbles



Levison et al. (2015)

Efficiency of growth

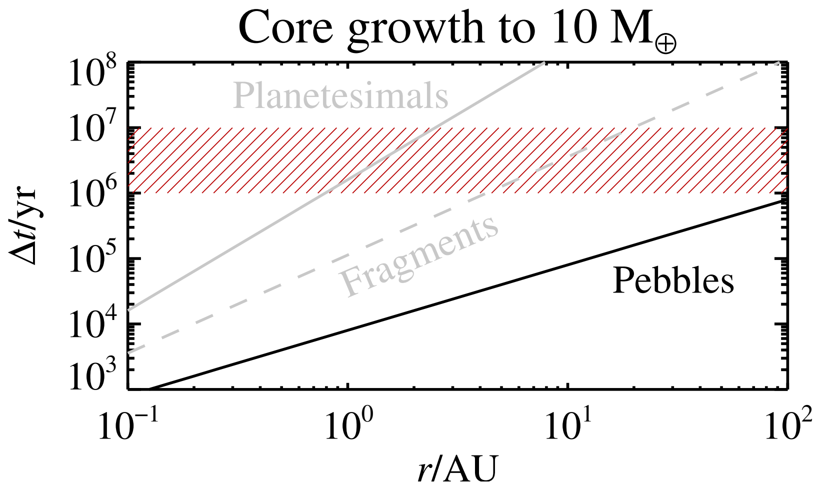
Bondi radius is the radius at which a particle is significantly deflected by gravity alone

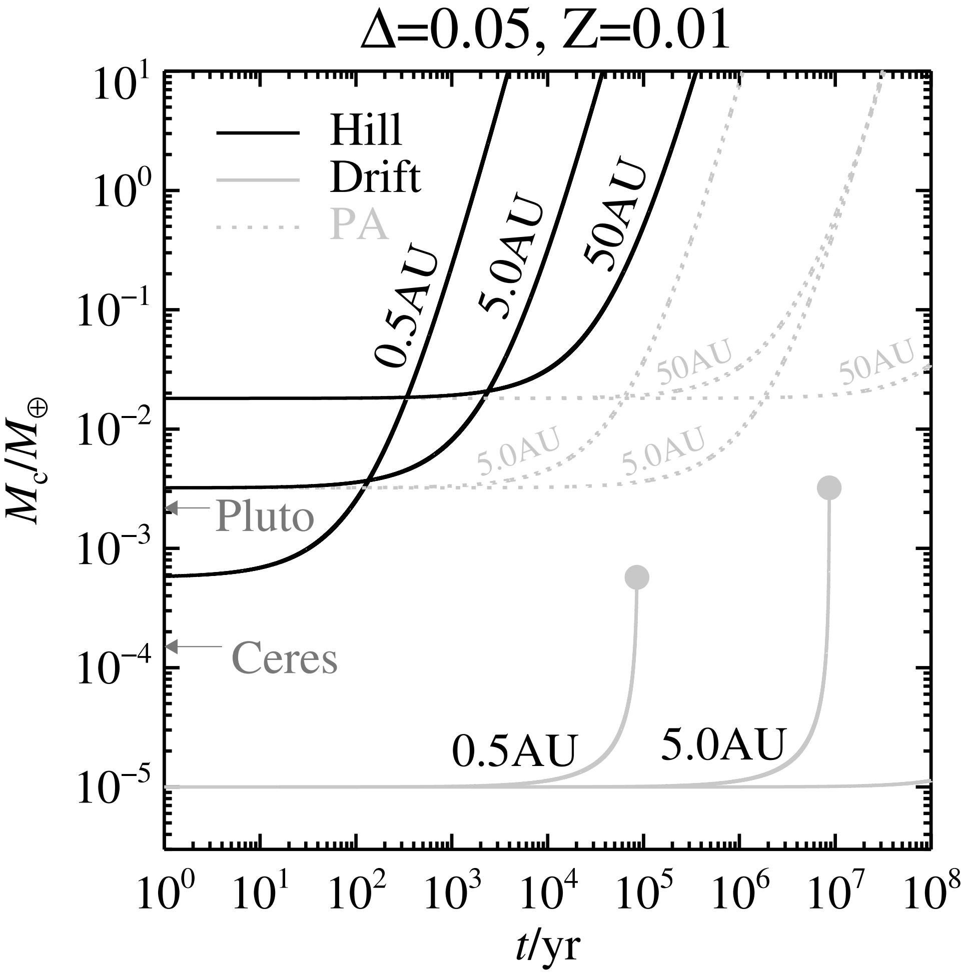


Lambrecht et al. (2012)

Giant planet cores can grow very quickly

Core growth can be achieved at Jupiter’s distance from the Sun during the nebular phase





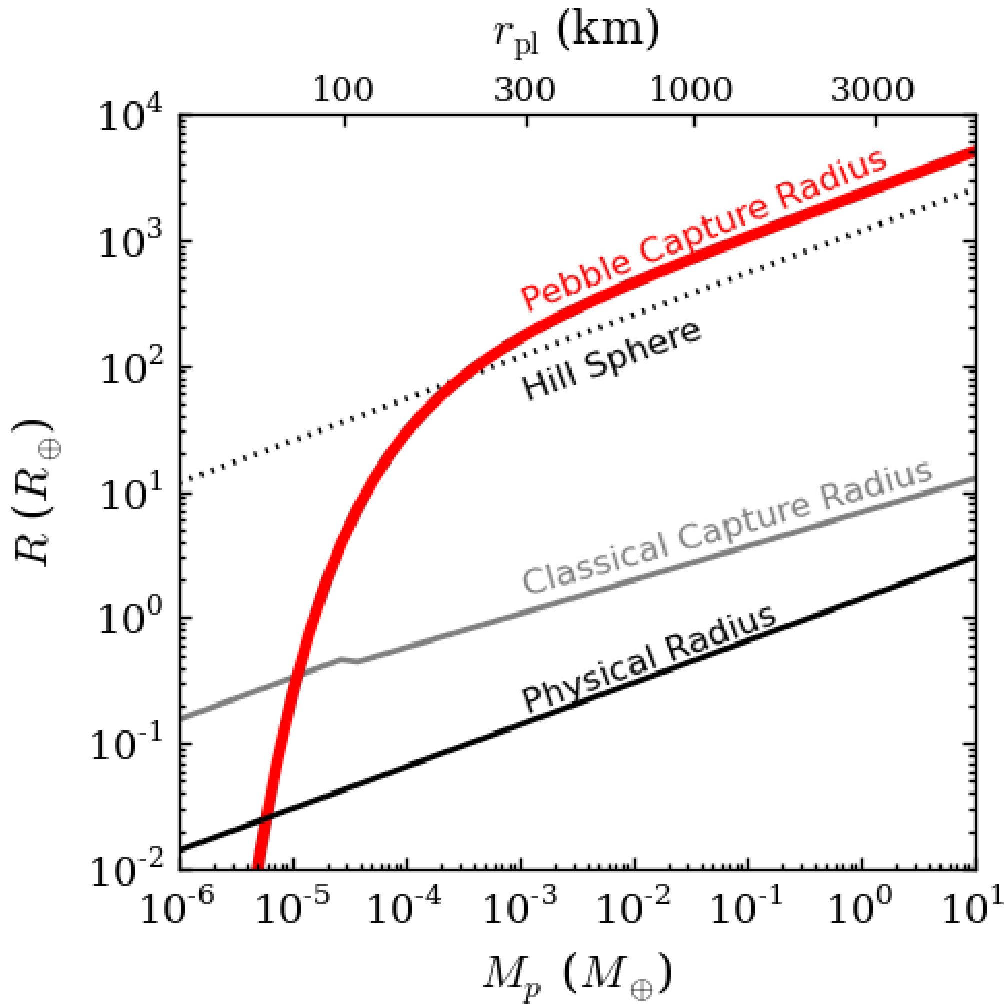
Lambrecht et al. (2012)

Pebble accretion cross-section

Pebble accretion is efficient because it enhances the cross-section of capture

AND

Likely more mass in pebbles due to growth barriers than in the planetesimal population



Levison et al. (2015)

Step 2 Complete!
Planetesimals to Embryos

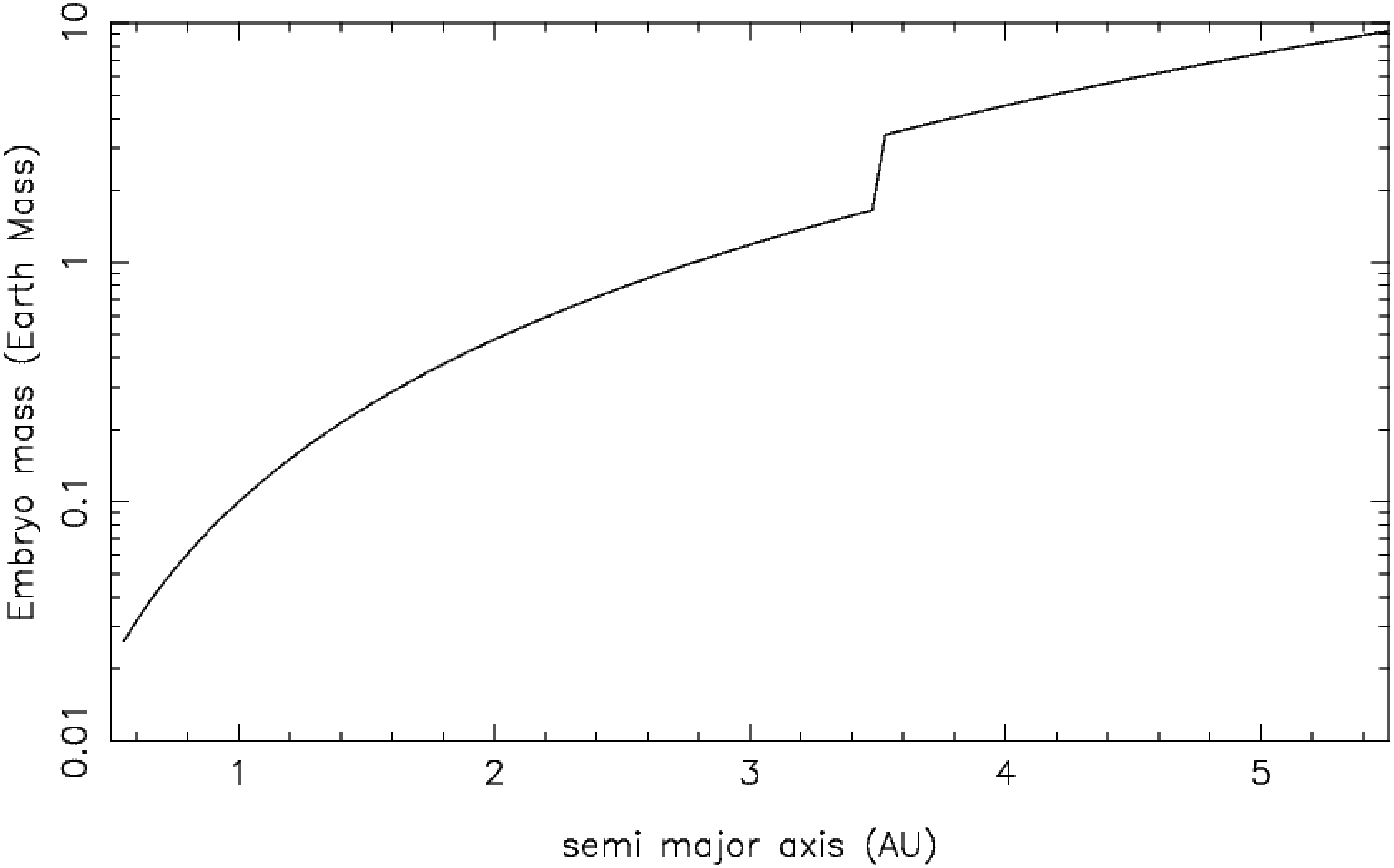
Pebble accretion is the only process put forward that can explain the growth rate of the giant planets, the great dichotomy and the formation of chondrites

Pebble accretion relies on the same aerodynamic drag mechanisms as radial drift and the streaming instability

Great Dichotomy of the Solar System

- Giant planets are ~100 times larger than the terrestrial planets
- Classical explanation is that giant planets lie exterior to the snowline so they accrete from silicates and ices
- But ices are only 50% of comets

No explanation for the great dichotomy



Morbidelli et al. (2015)

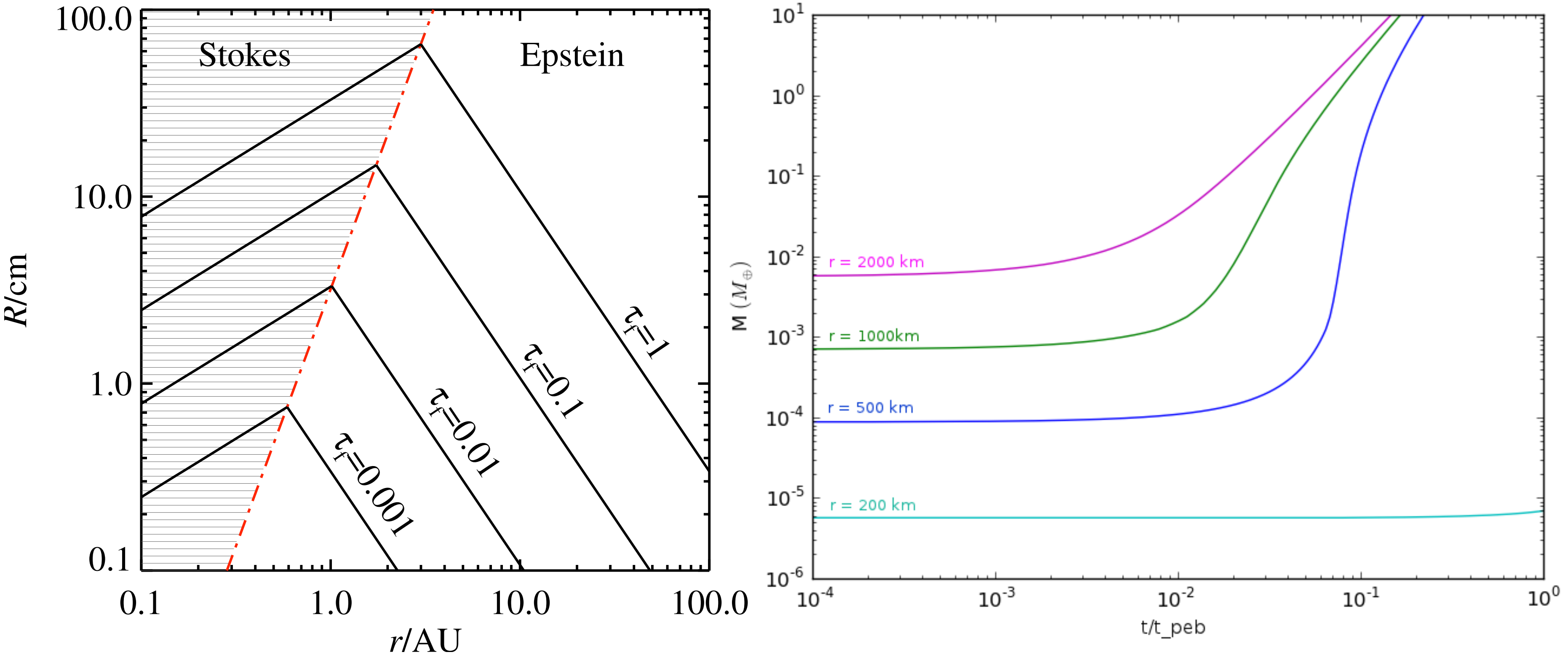
A simple hypothesis

Pebbles in the outer solar system are 50% ice and reach 10 cm to 10 m in size

The 50% silicates in those pebbles are in 0.1 mm to 1 cm grains

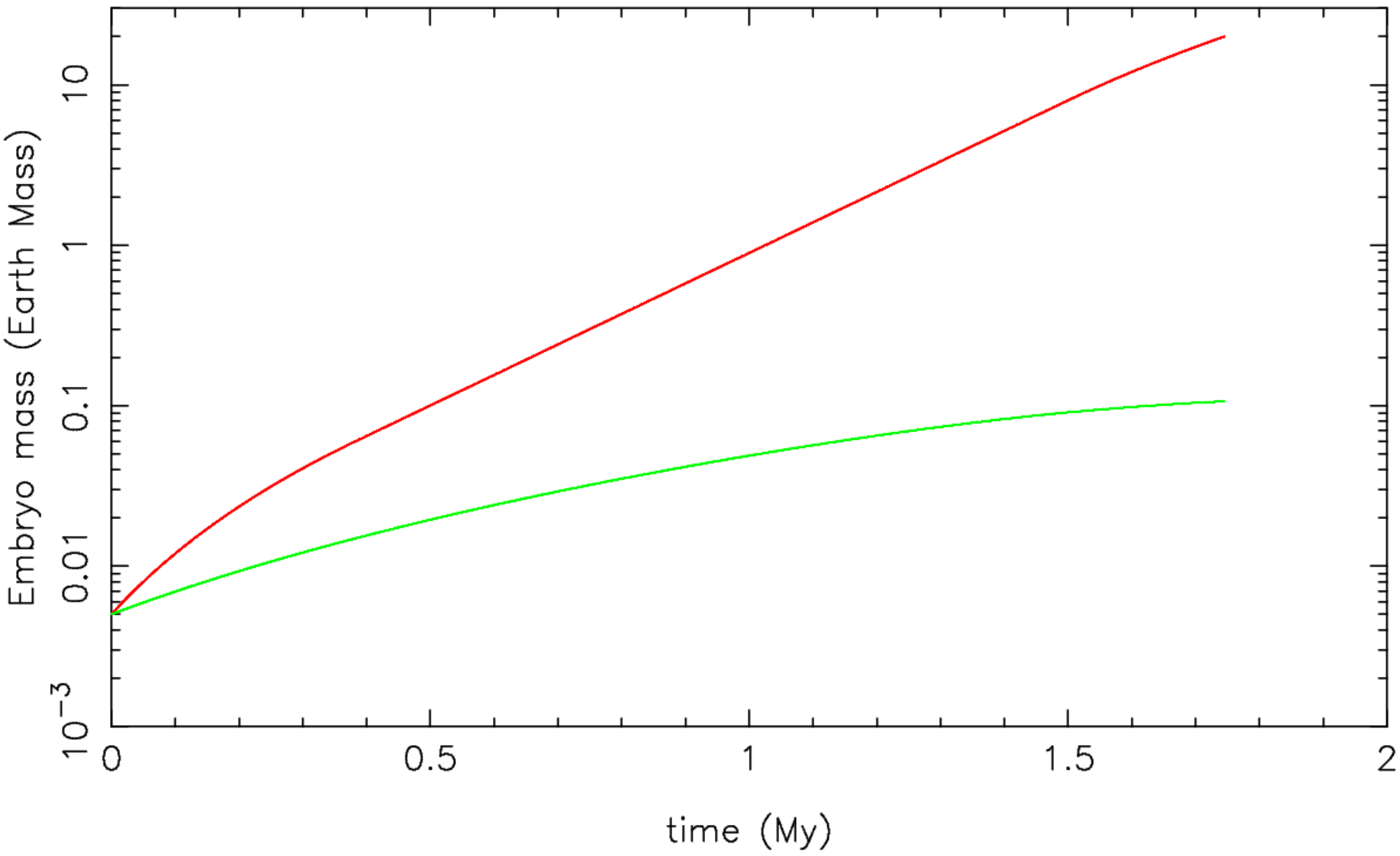
When outer solar system pebbles reach the ice line, the ice sublimate

Transition mass



Transition mass is a function of properties of the pebbles as well as location and other disk properties

It works



Explanation for the great dichotomy

Pebble accretion is conducted inefficiently in the inner Solar System, while it is conducted efficiently in the outer Solar System

The factor of two in mass is relatively unimportant but the change in the mechanical properties of ice versus rock are

Lastly, the inner Solar System pebbles are chondrule-sized …

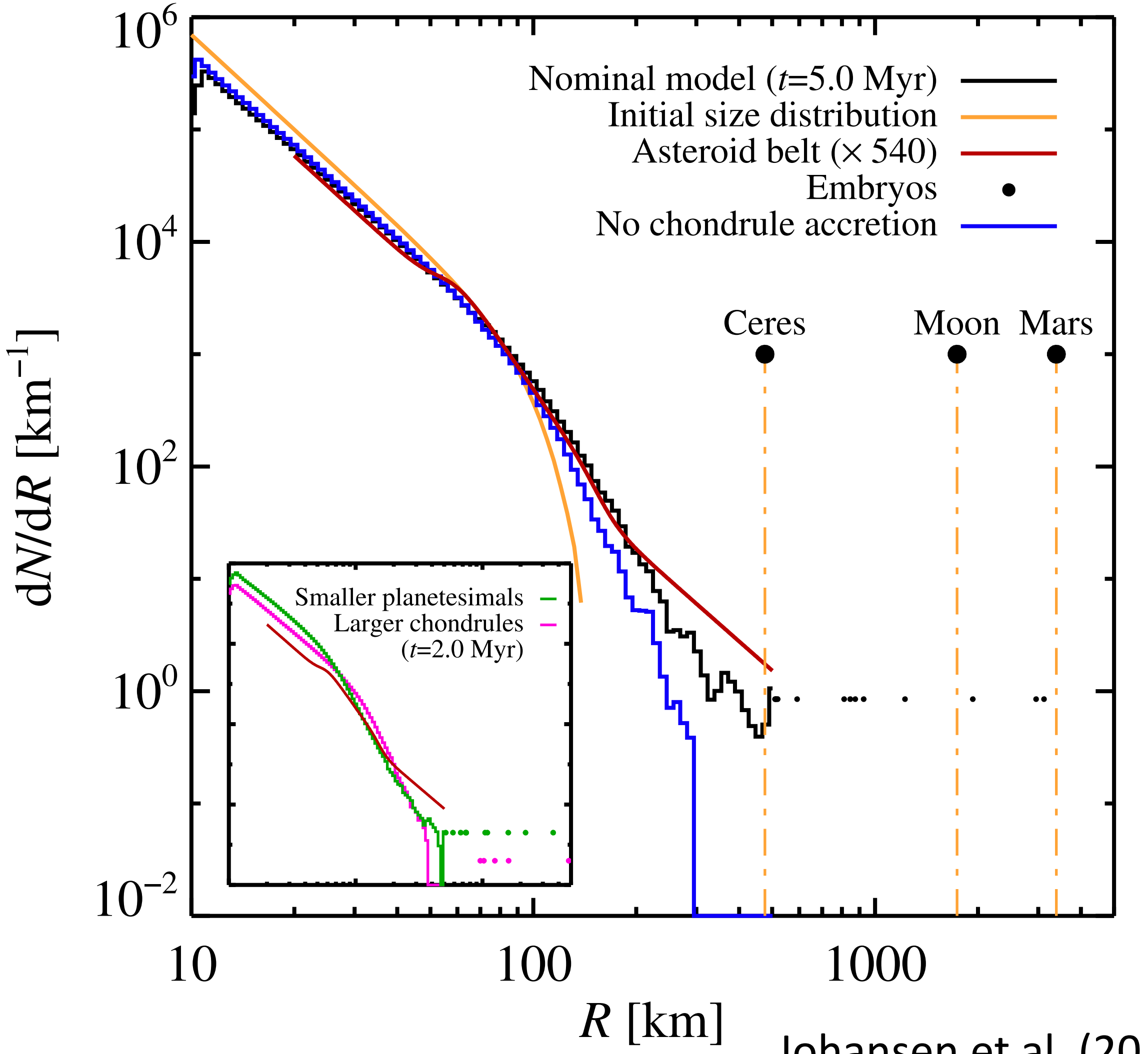
Chondrules

Roughly mm-sized melt spherules

If they are plentiful in the inner Solar System, then they will be accreted by large and small embryos alike

Pebble accretion in the asteroid belt

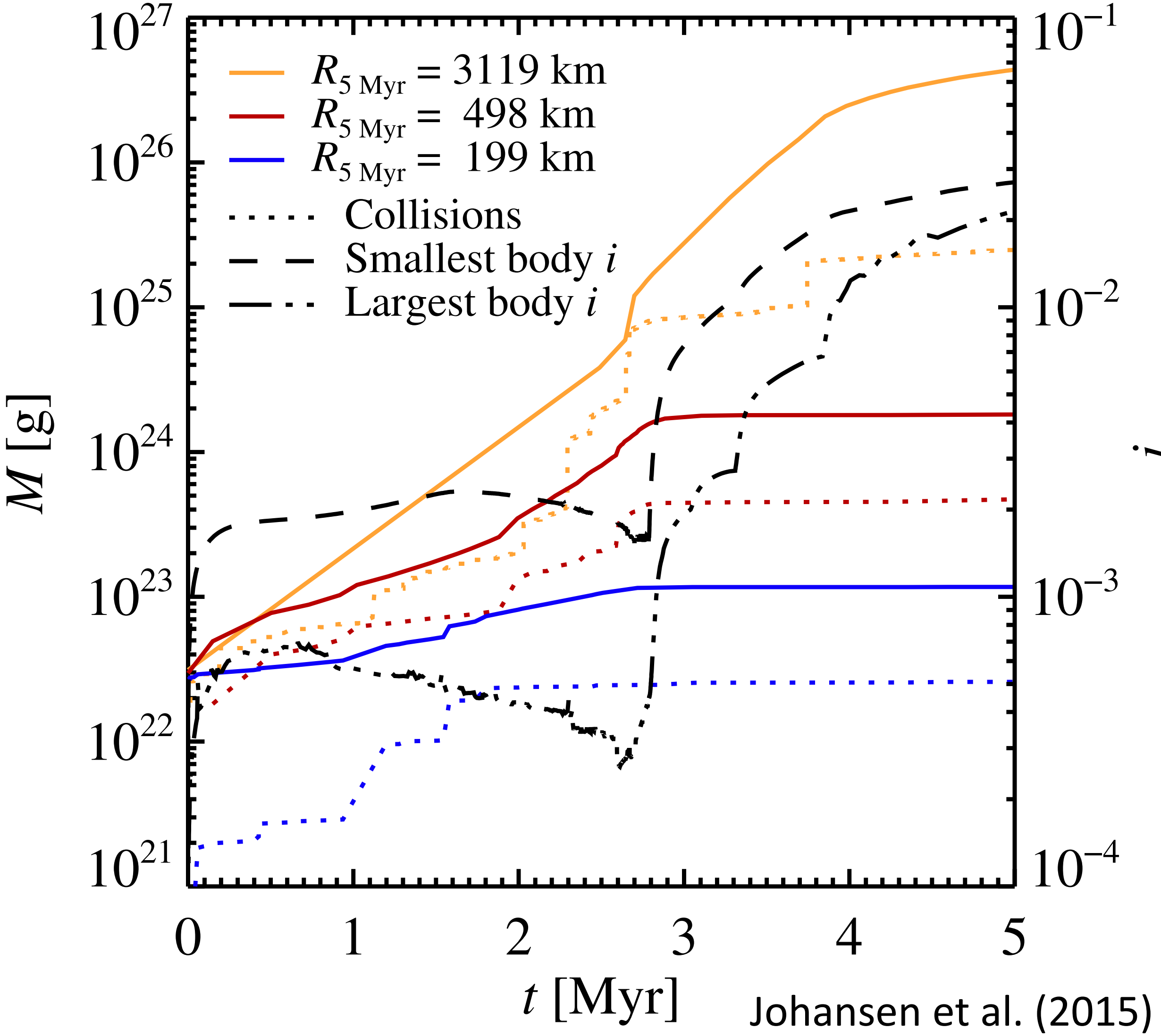
If chondrules are pebbles then they may explain the size distribution in the asteroid belt



Johansen et al. (2015)

Pebble accretion in the asteroid belt

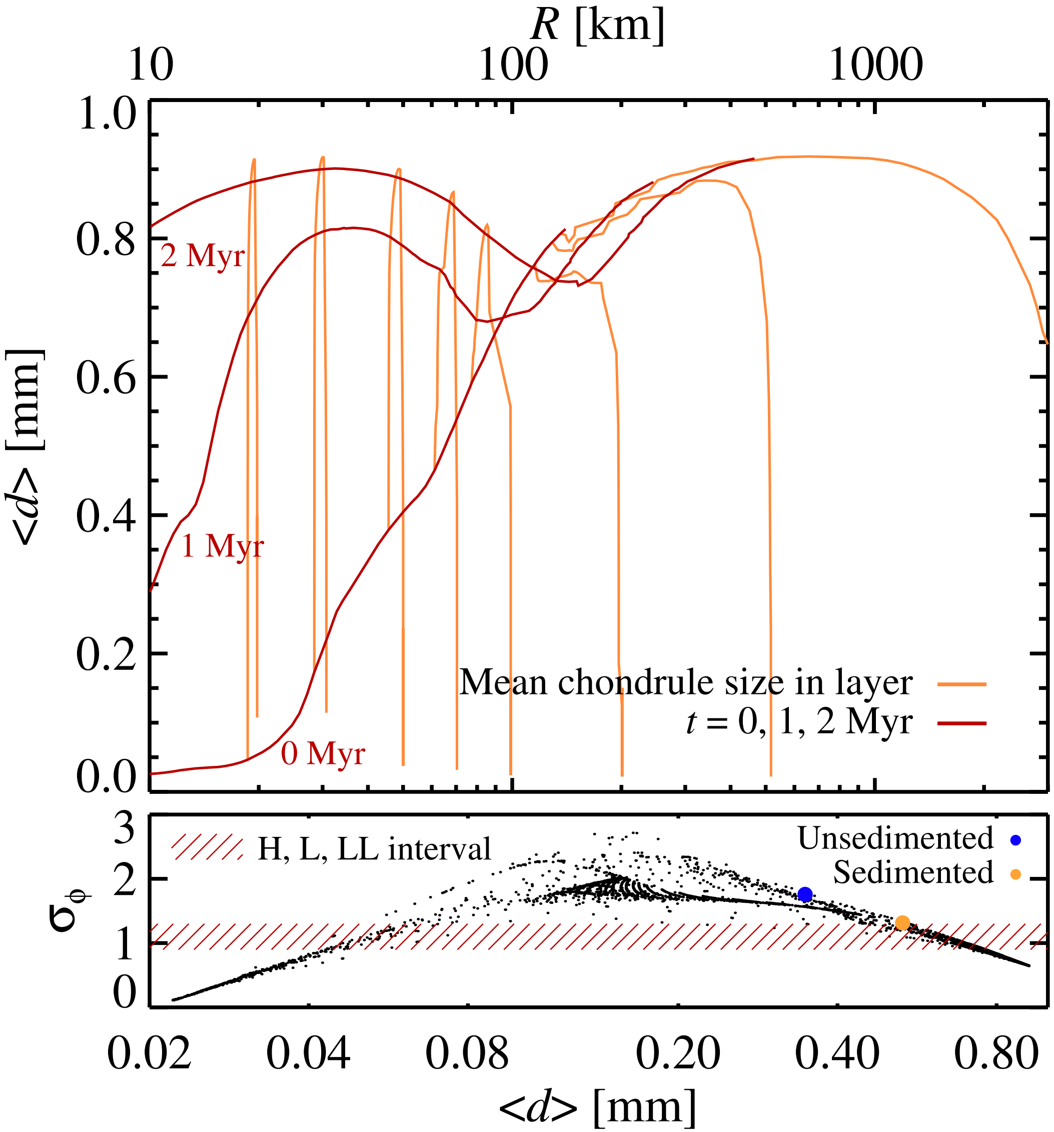
If true then chondrules would make up most of the mass of large asteroids and hence of the belt



Johansen et al. (2015)

Pebble accretion in the asteroid belt

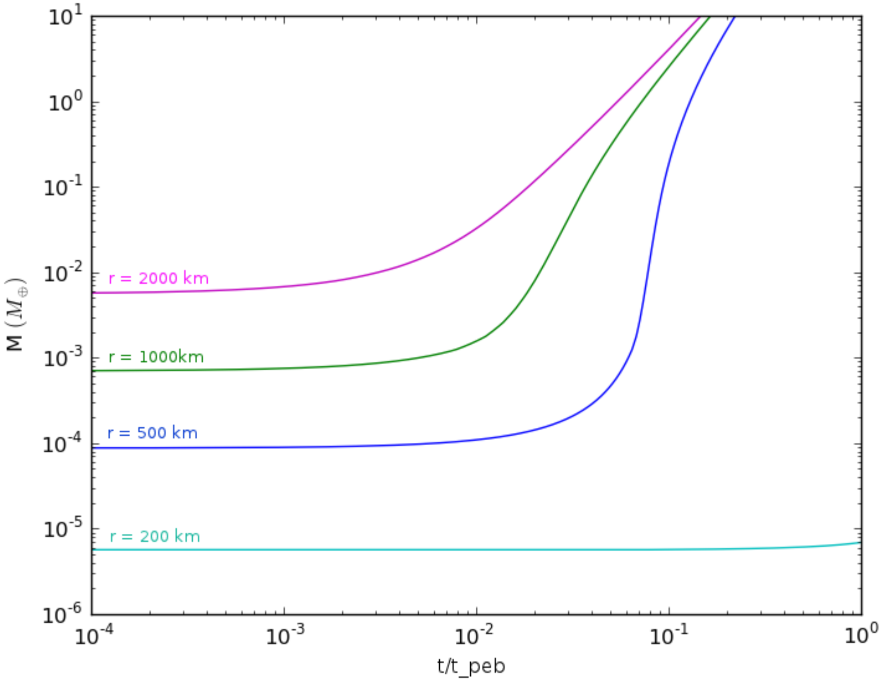
Furthermore, pebble accretion is an aerodynamic process that naturally sorts the chondrules according to size



Johansen et al. (2015)

Transition mass

For most nominal disks, this transition mass is around a few hundred km for optimal pebble sizes

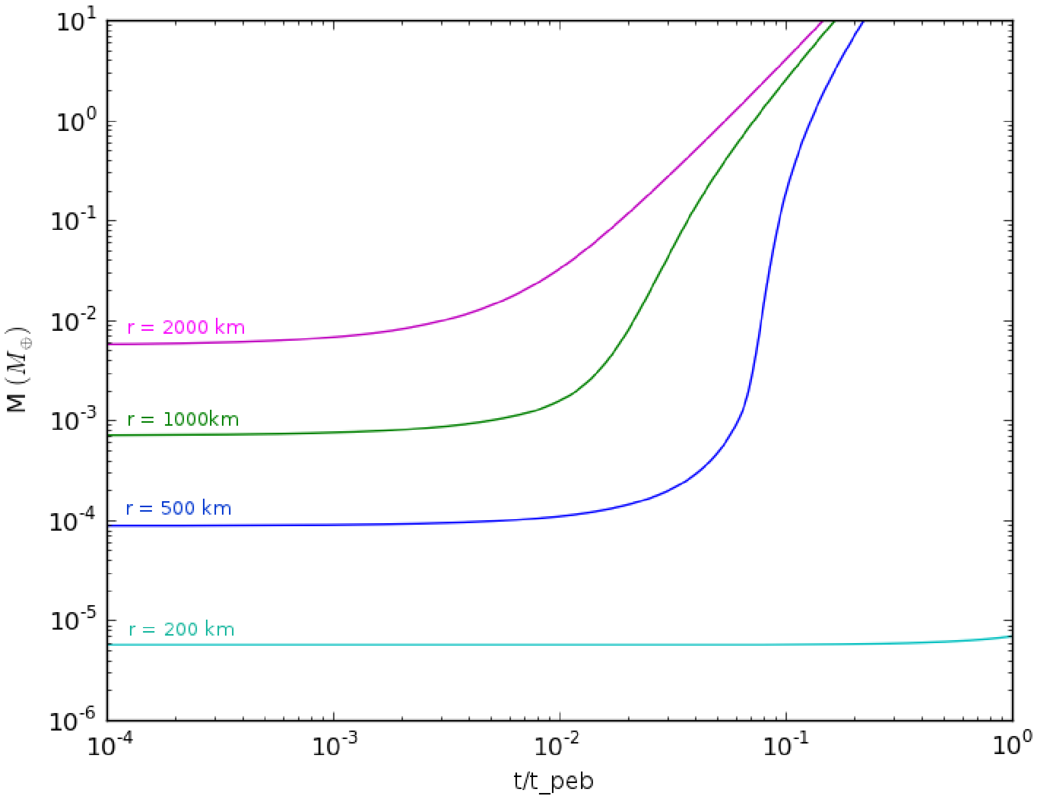


Levison et al. (2015)

Larger for less optimal disk

Transition mass

Threshold transition mass divides planetesimals that will grow to embryos from those that won’t

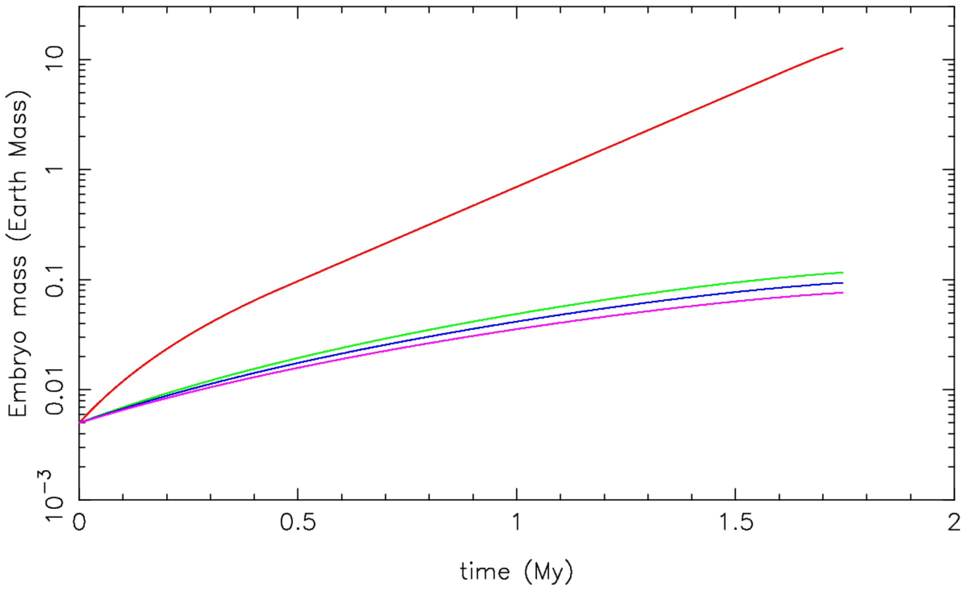


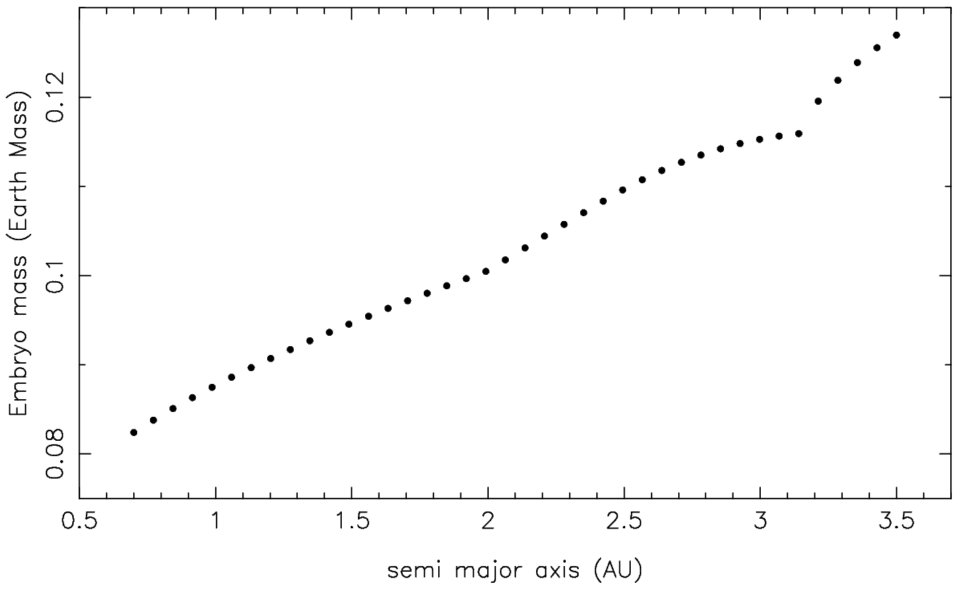
Levison et al. (2015)

This creates a bimodal mass disk of hundred km objects and those that grow due to pebble accretion

Return to great dichotomy

Using a sophisticated pebble growth and disk model within the assumptions of the great dichotomy and assuming ~40 seed embryos created by the streaming instability





Bi-modal mass distribution

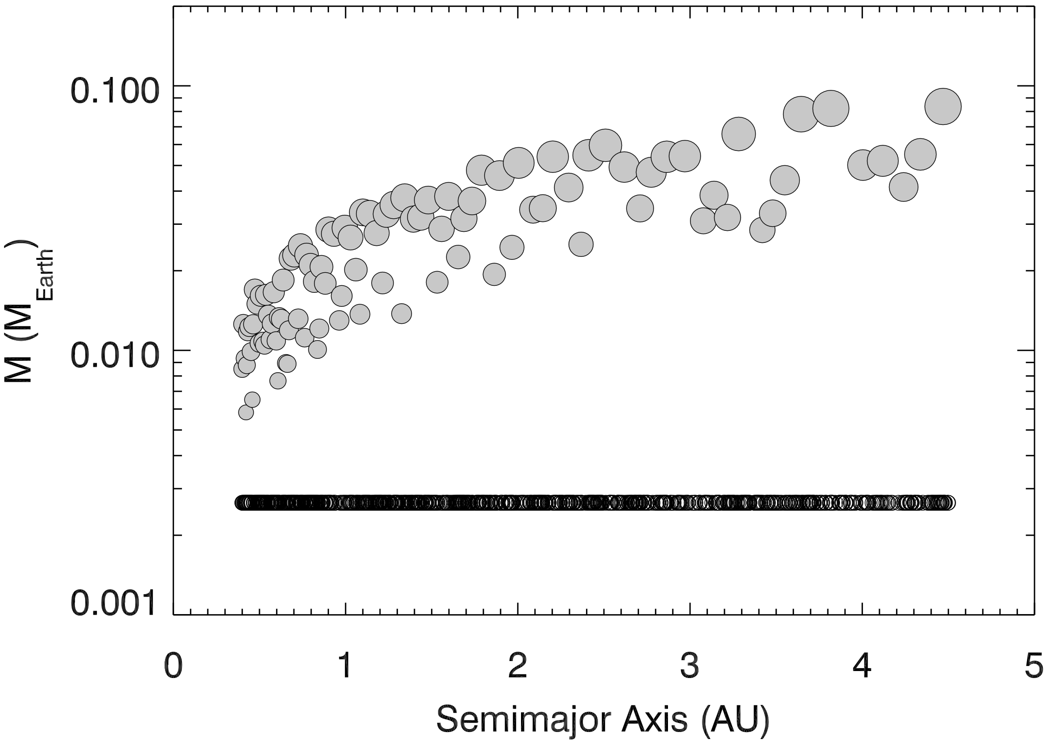
Incredibly, the streaming instability and pebble accretion could create a bi-modal mass distribution of 100 km-sized planetesimals and Mars-mass embryos

This is very similar to the bi-modal mass distribution created by runaway and oligarchic growth!

Standard model for terrestrial planet formation

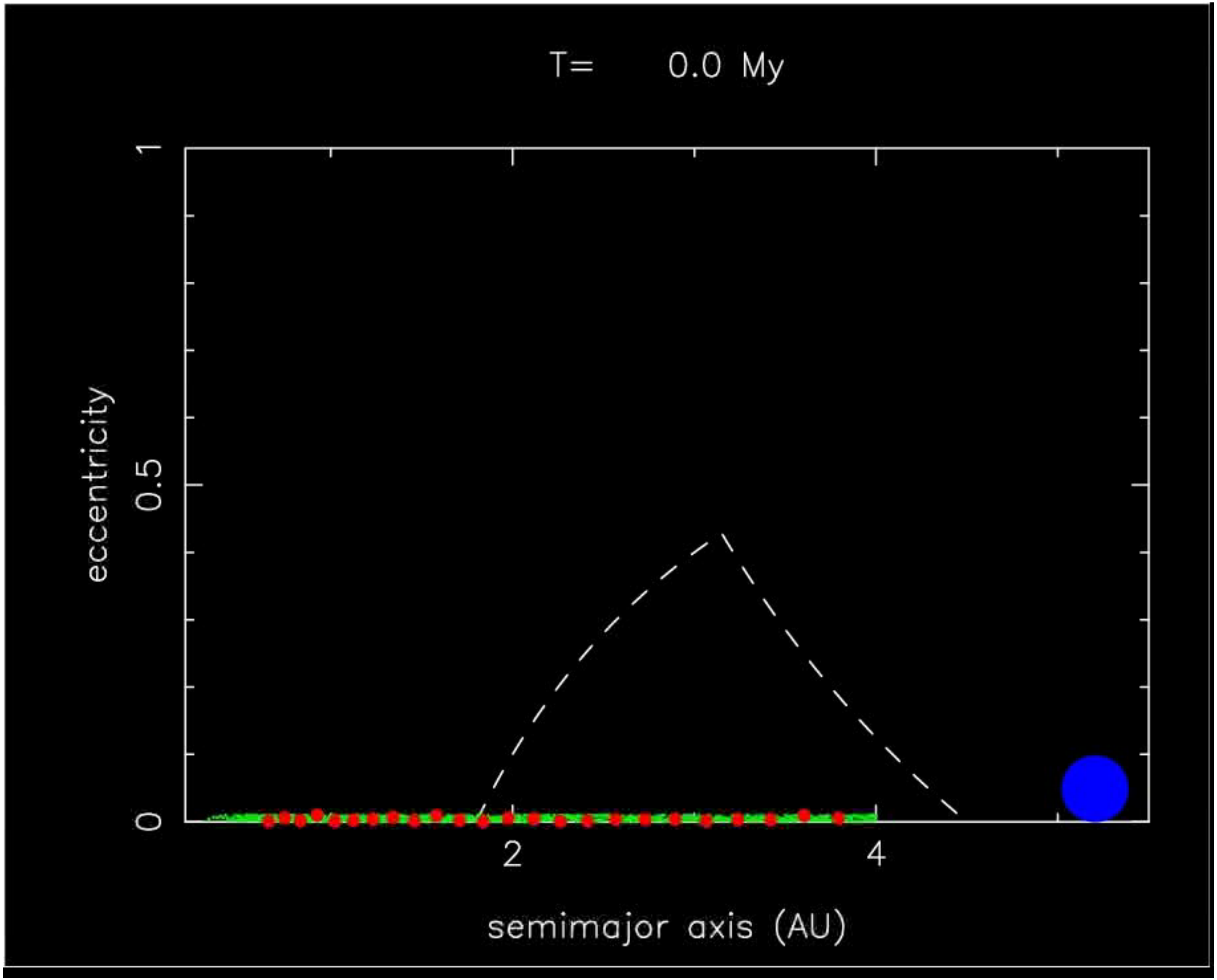
Bimodal mass disk that extends from an inner edge to Jupiter

Jupiter and the other giant planets on fixed orbits



Raymond et al. (2009)

From embryos to terrestrial planets

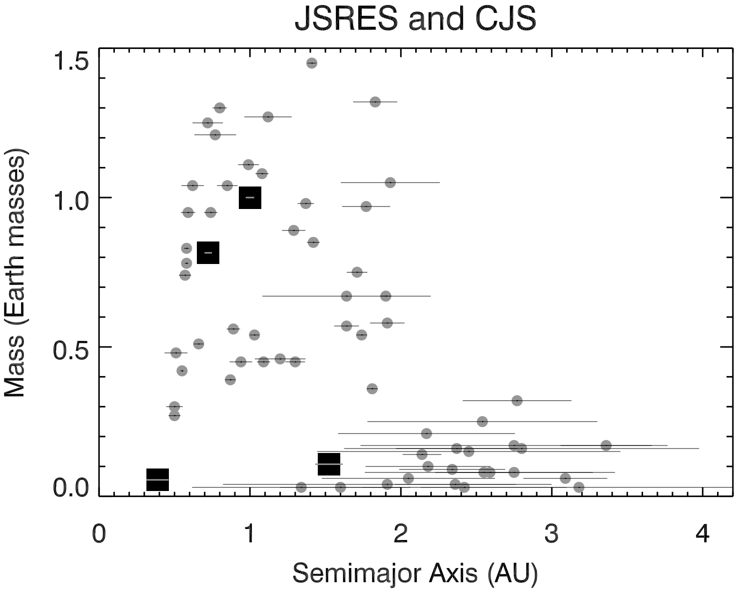


O’Brien, Morbidelli and Levison (2006)

Final Standard Model Outcomes

Successes:

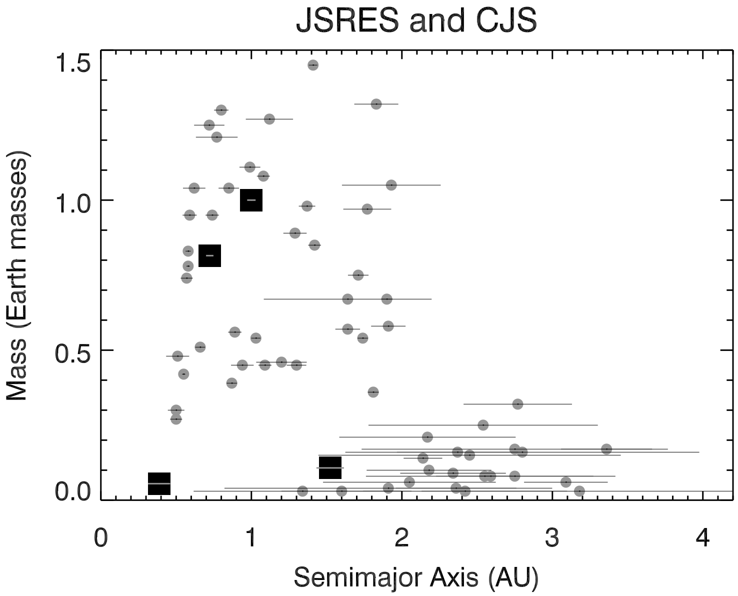
- Formation of a few terrestrial planets in the terrestrial planet zone
- The most massive planets are about an Earth mass
- Good orbits (eccentricity and inclination excitation)
- Roughly correct accretion timescale for the Earth (tens of My)
- Giant impacts are typical, several with geometries compatible with the Moon-forming event
- Delivery of water-rich bodies from the asteroid belt to the Earth



Final Standard Model Outcomes

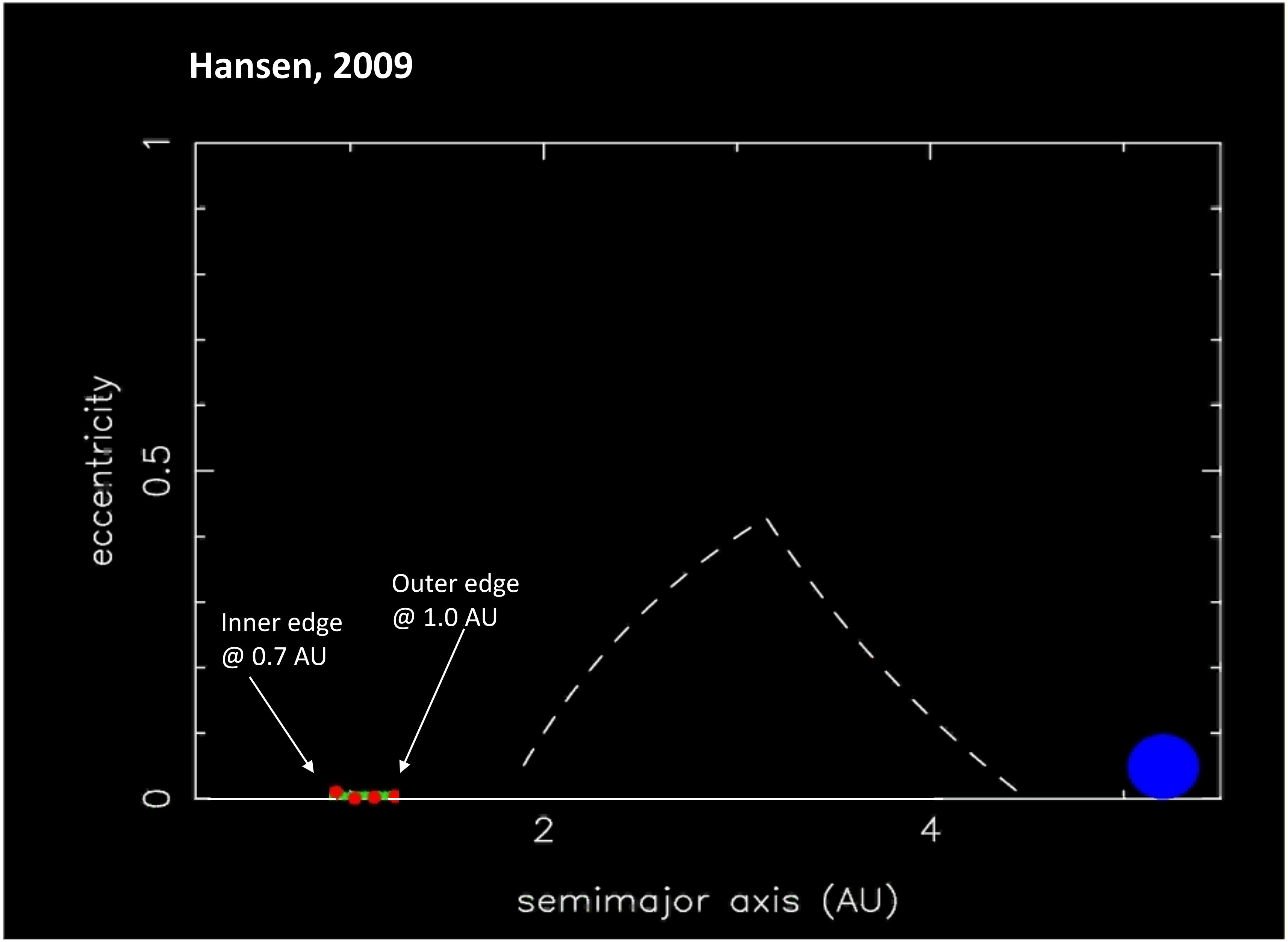
Failures:

- Planets at the location of Mars are too massive by an order of magnitude
- Persistent problem despite many different initial conditions (embryo number, giant planet orbits)



Raymond et al. (2009)

Truncated disk

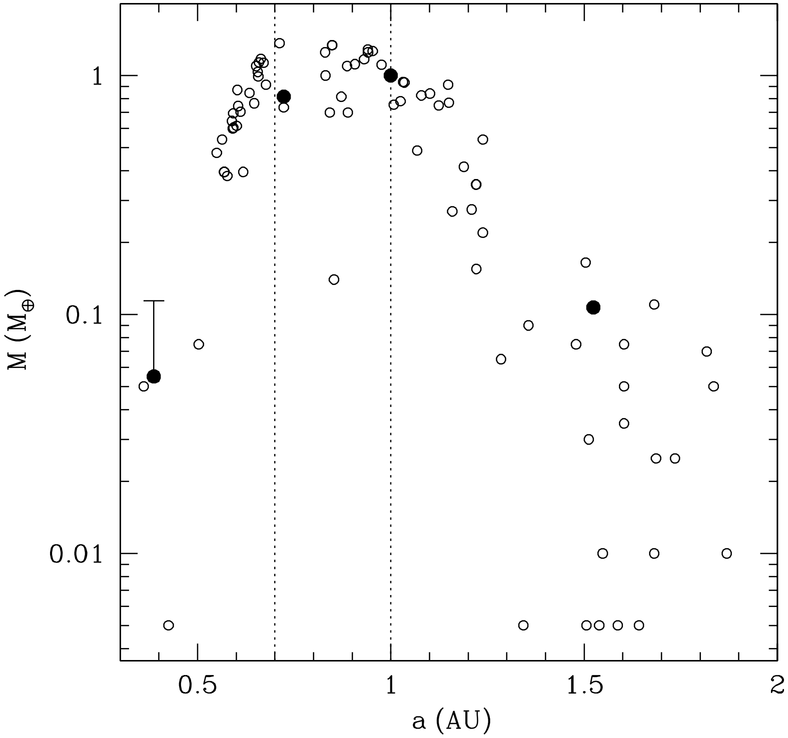


Hansen(2009)

Truncated disk outcomes

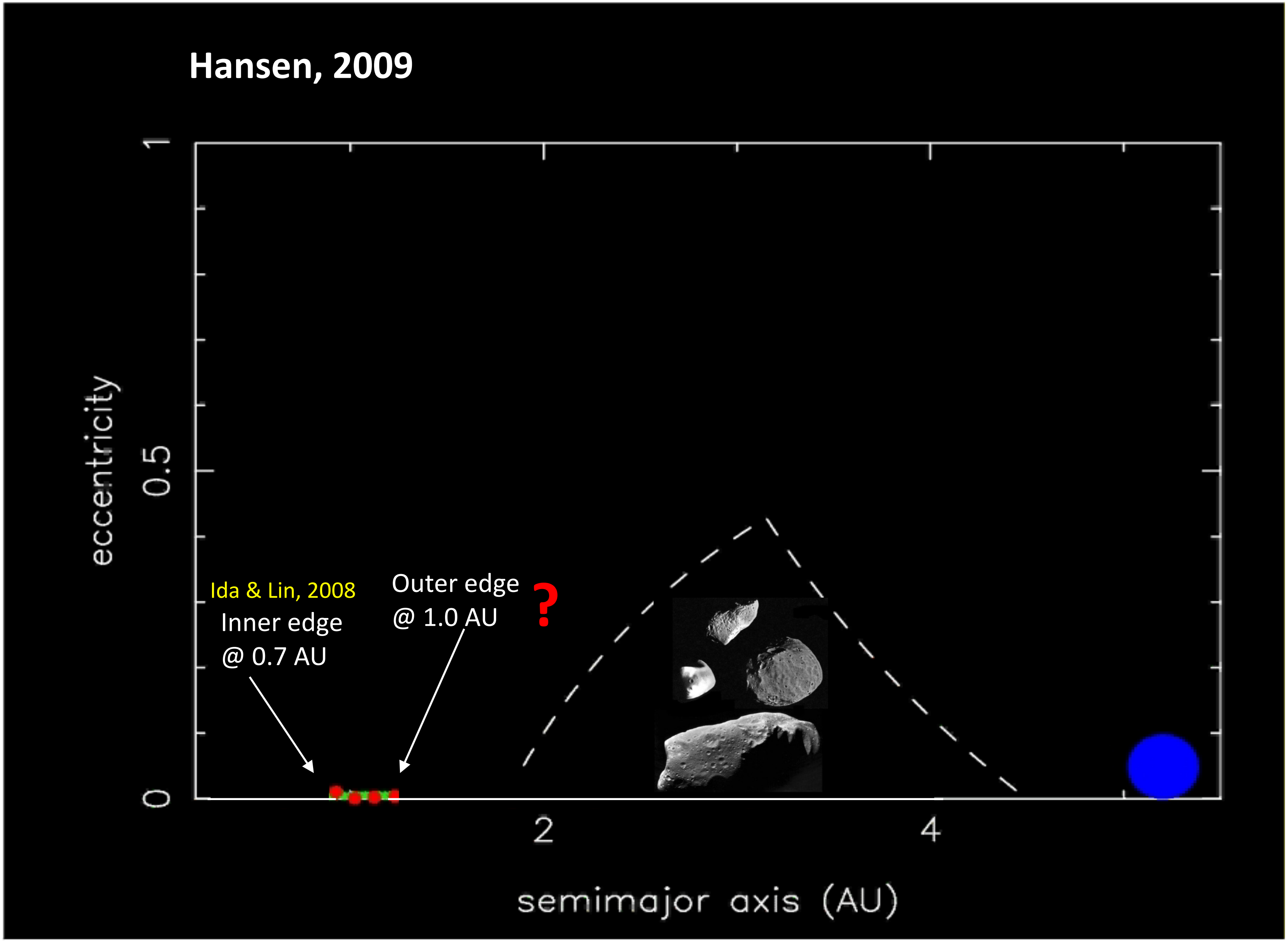
- Still match successes of the Standard Model
- Now, Mars analogs exist

What causes the truncation?



Hansen (2009)

Truncated disk



Hansen, 2009

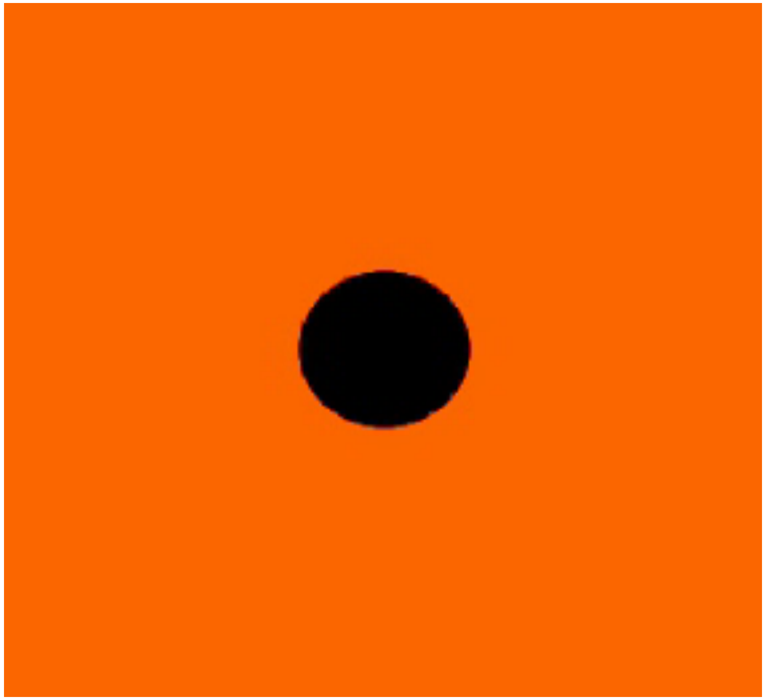
Ida & Lin, 2008
Inner edge
@ 0.7 AU

Outer edge
@ 1.0 AU

?

Hansen(2009)

Giant planets migrate

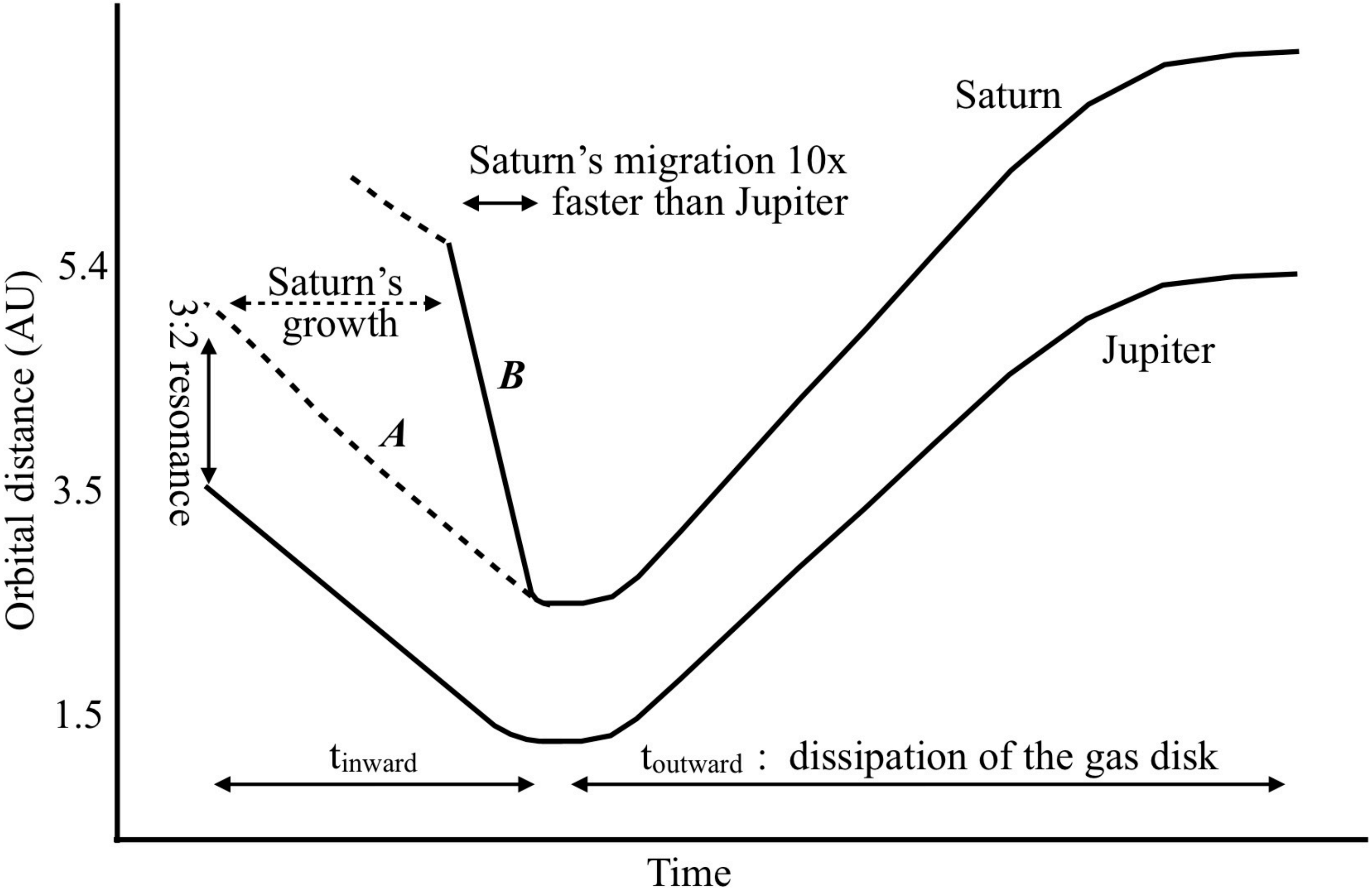


- Type II migration explains the origin of Hot Jupiters

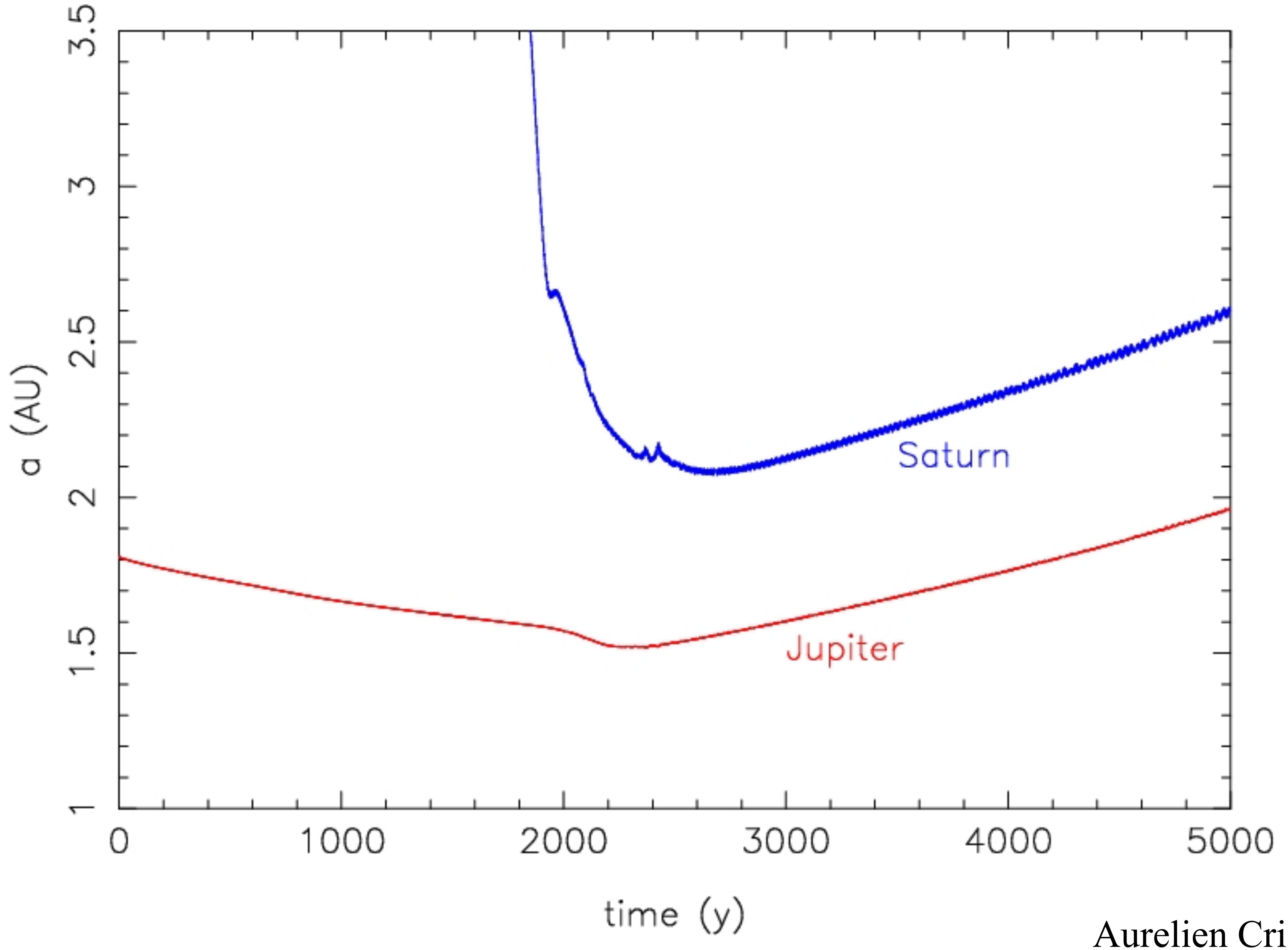
  Why don't we have a Hot Jupiter? What happened?

The Grand Tack scenario

Consistent with hydro-dynamical simulations by Masset & Snellgrove (2001), Morbidelli & Crida (2007), and Pierens & Nelson (2008)

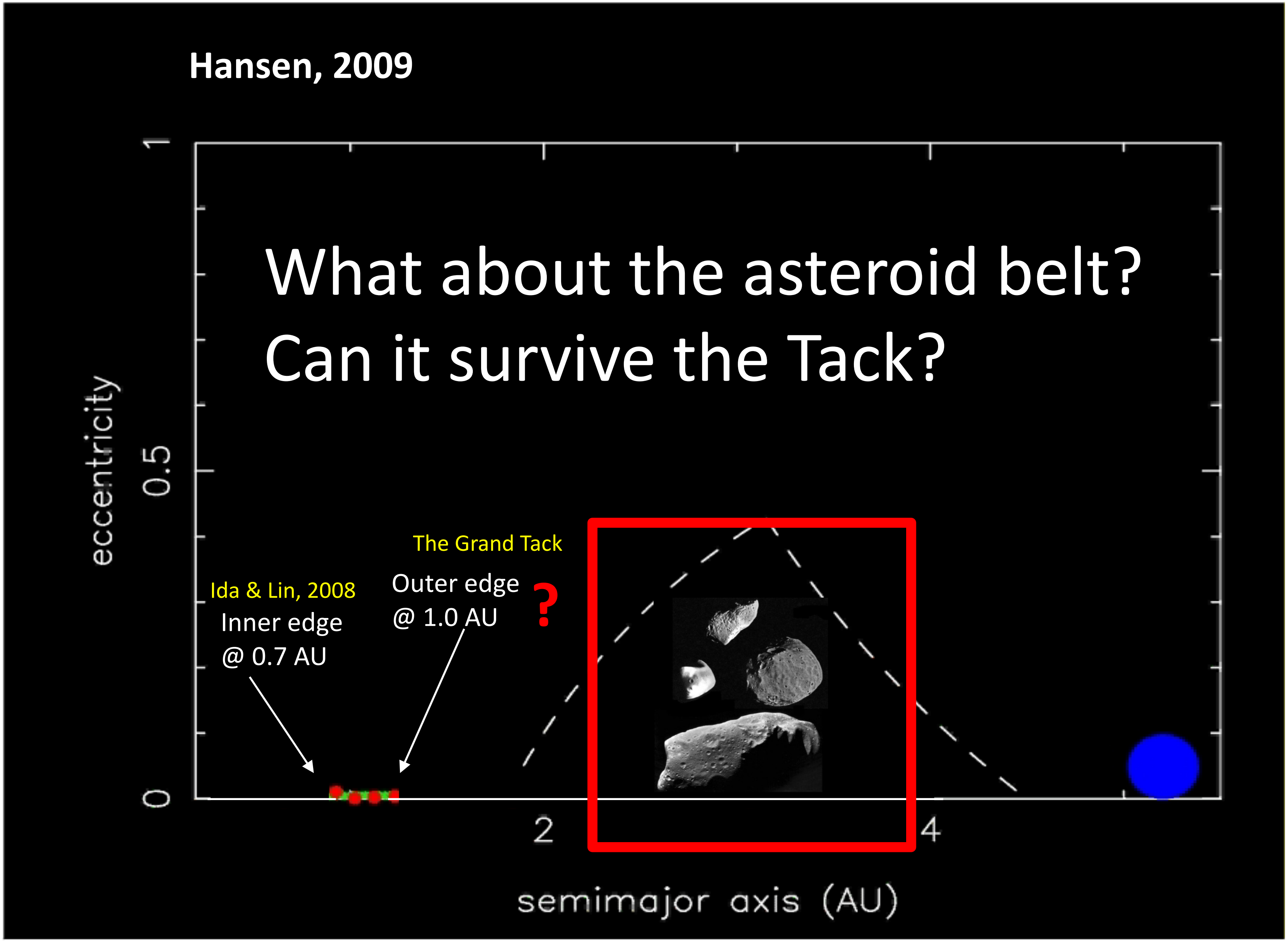


The Grand Tack!



Aurelien Crida

Truncated disk



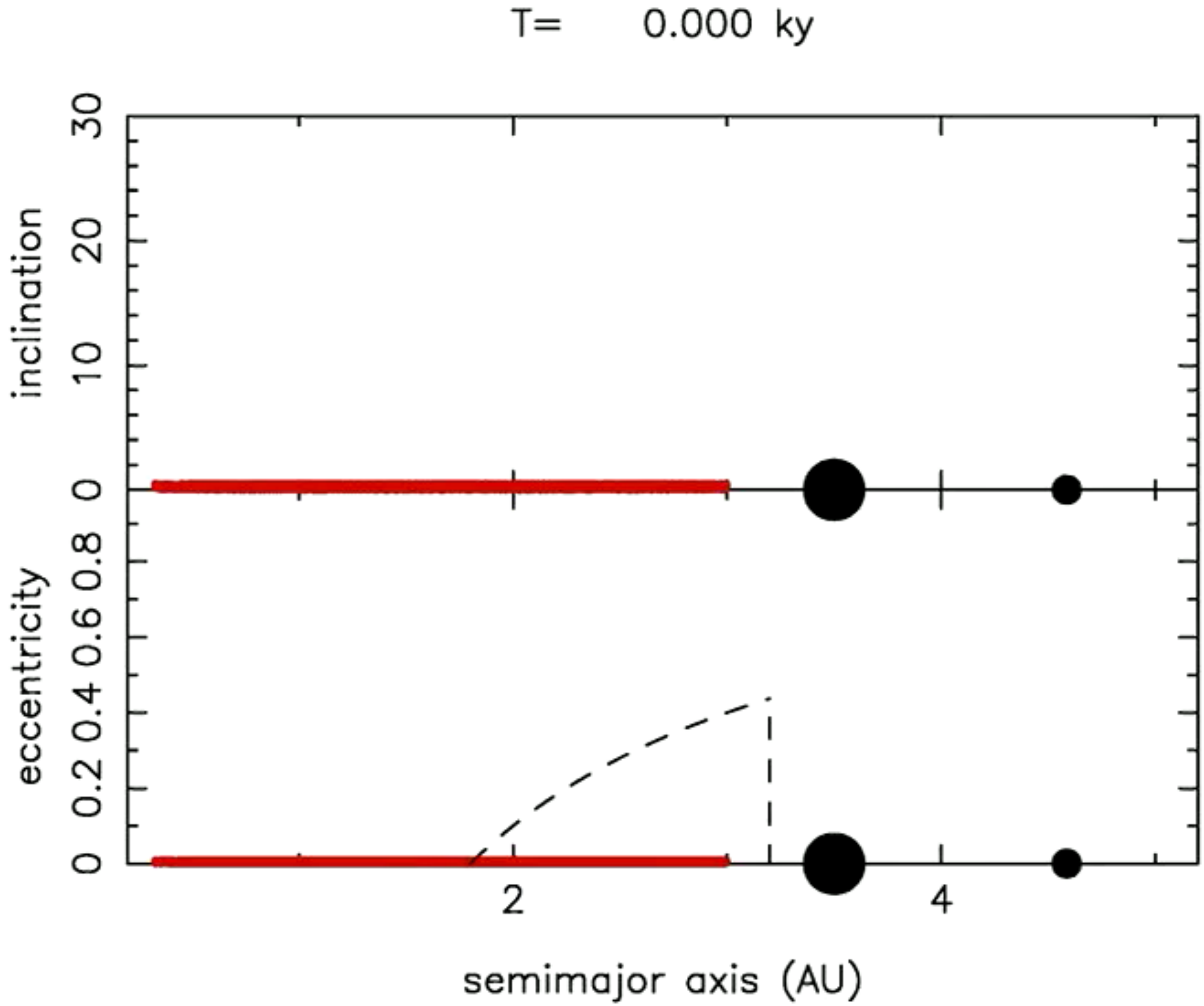
What about the asteroid belt?
Can it survive the Tack?

Ida & Lin, 2008
Inner edge
@ 0.7 AU

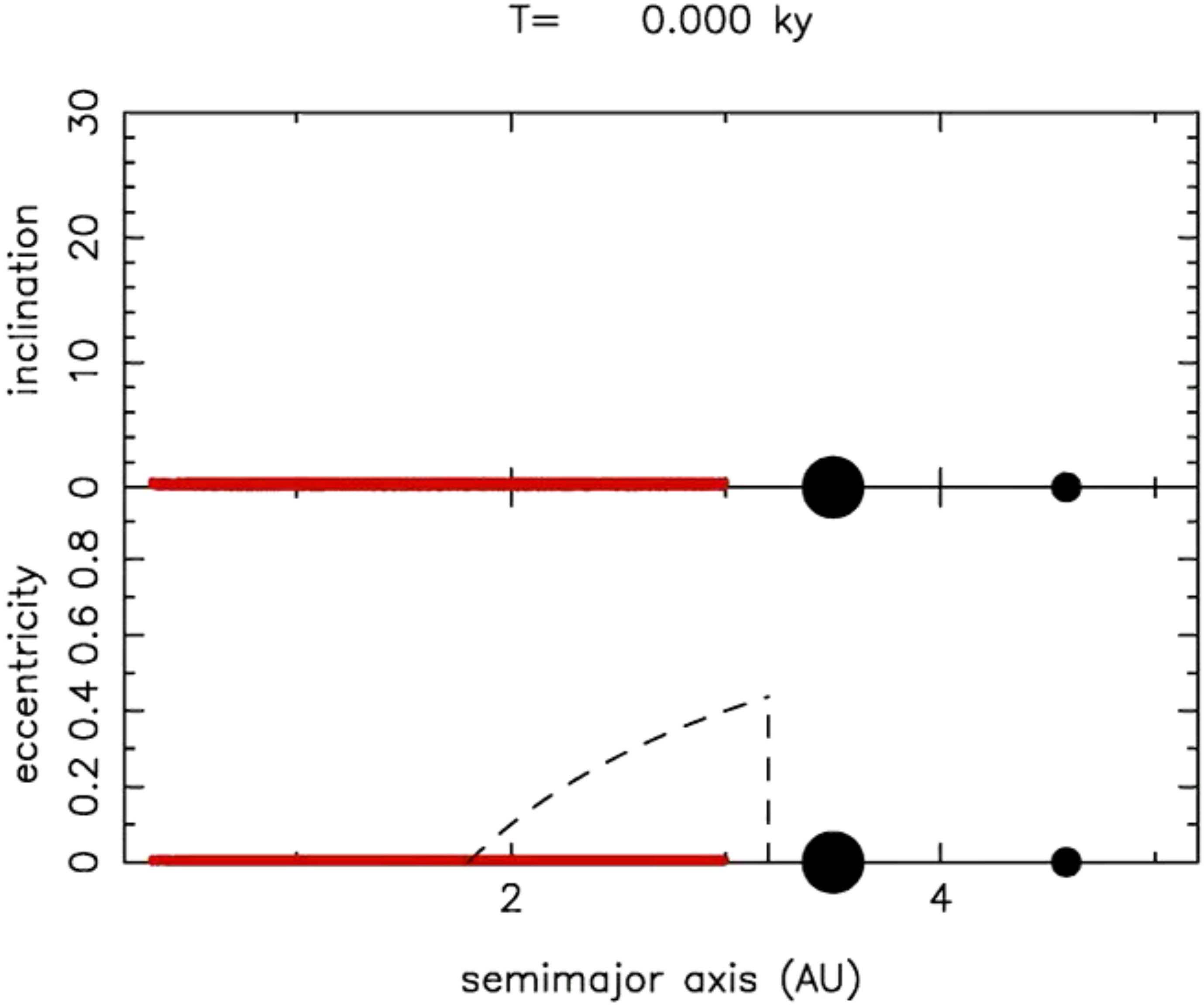
The Grand Tack
Outer edge
@ 1.0 AU
?

Hansen(2009)

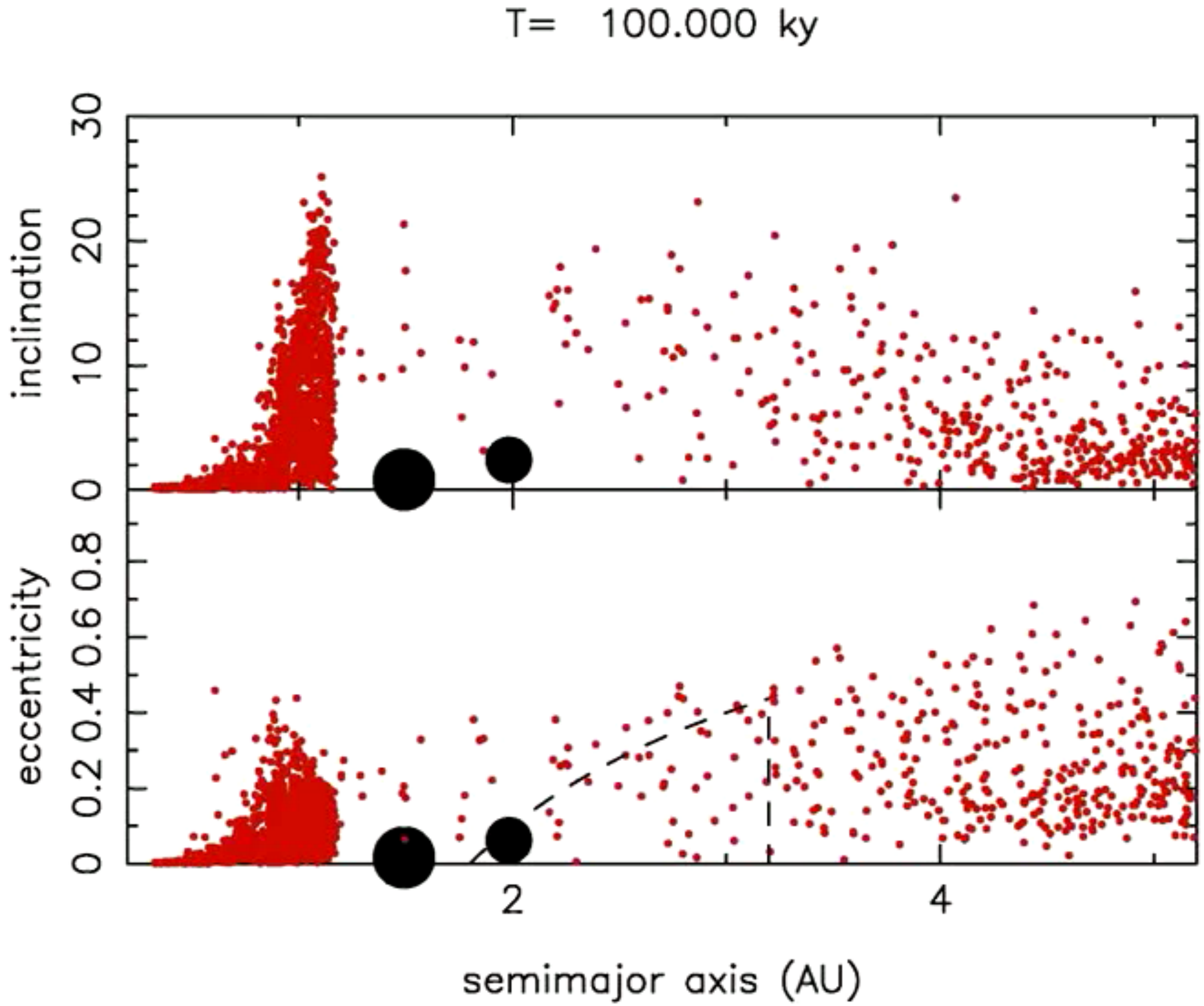
Walsh et al., 2011



Walsh et al., 2011



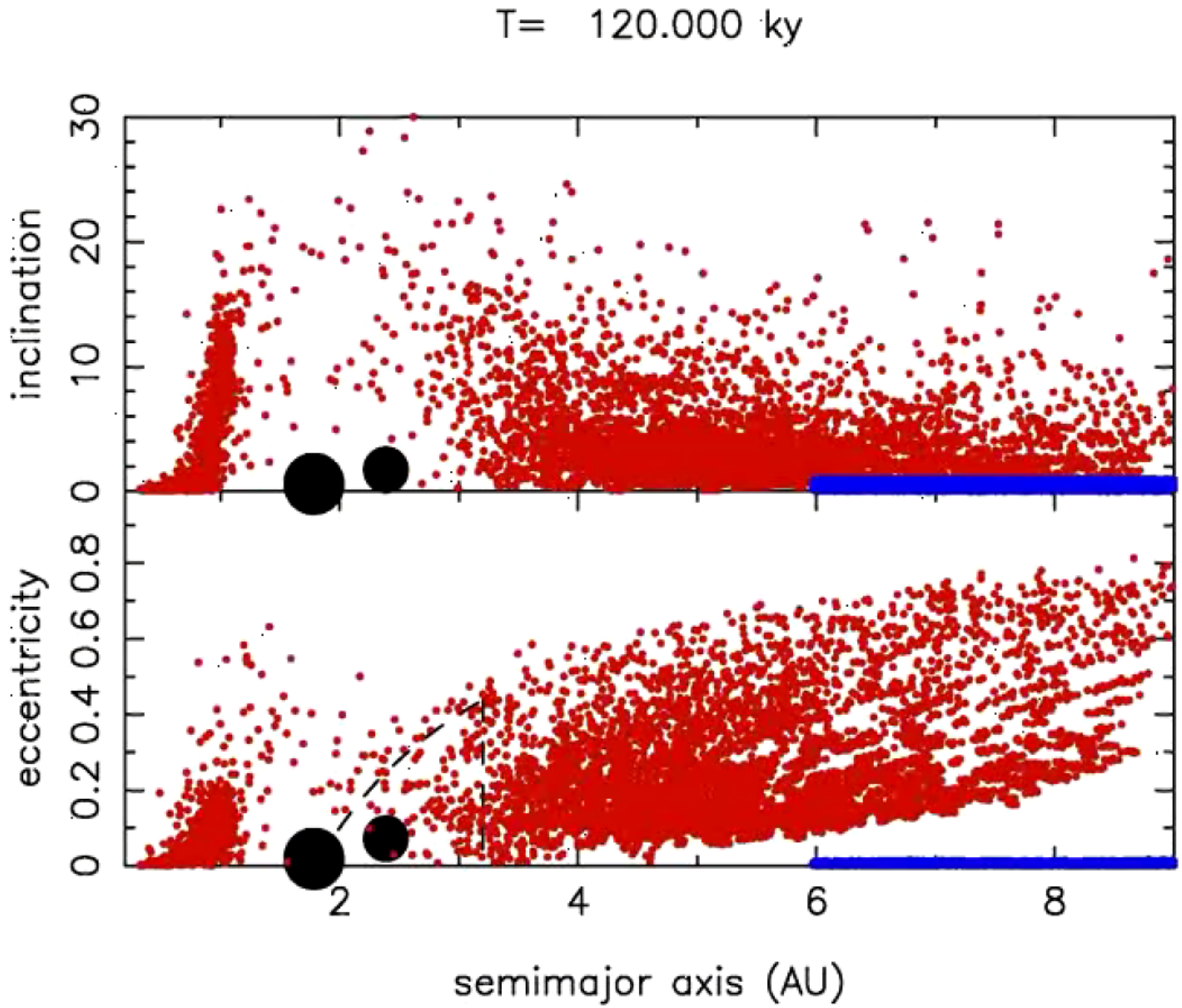
Walsh et al., 2011



Walsh et al., 2011

● S-type

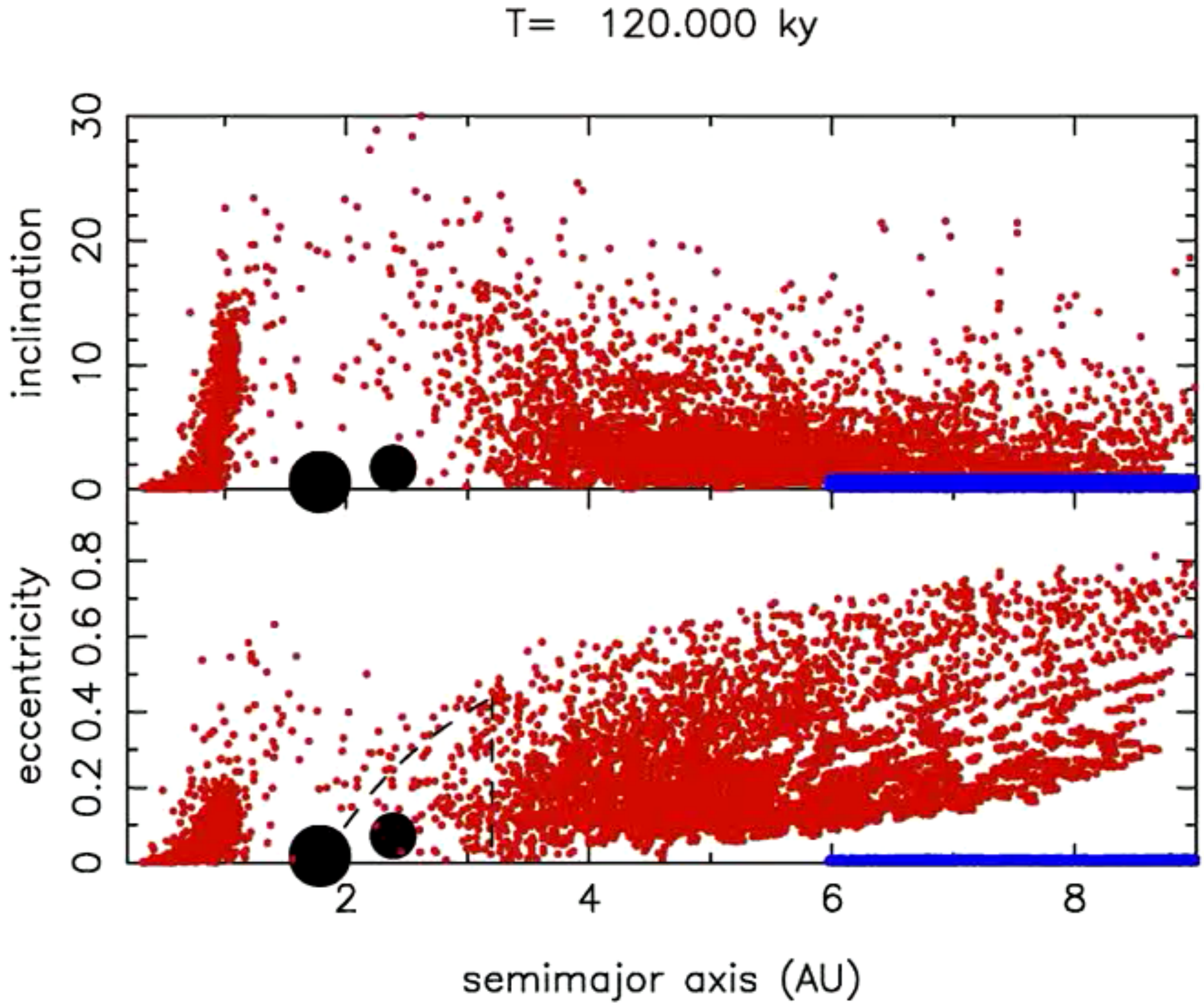
● C-type



Walsh et al., 2011

● **S-type**

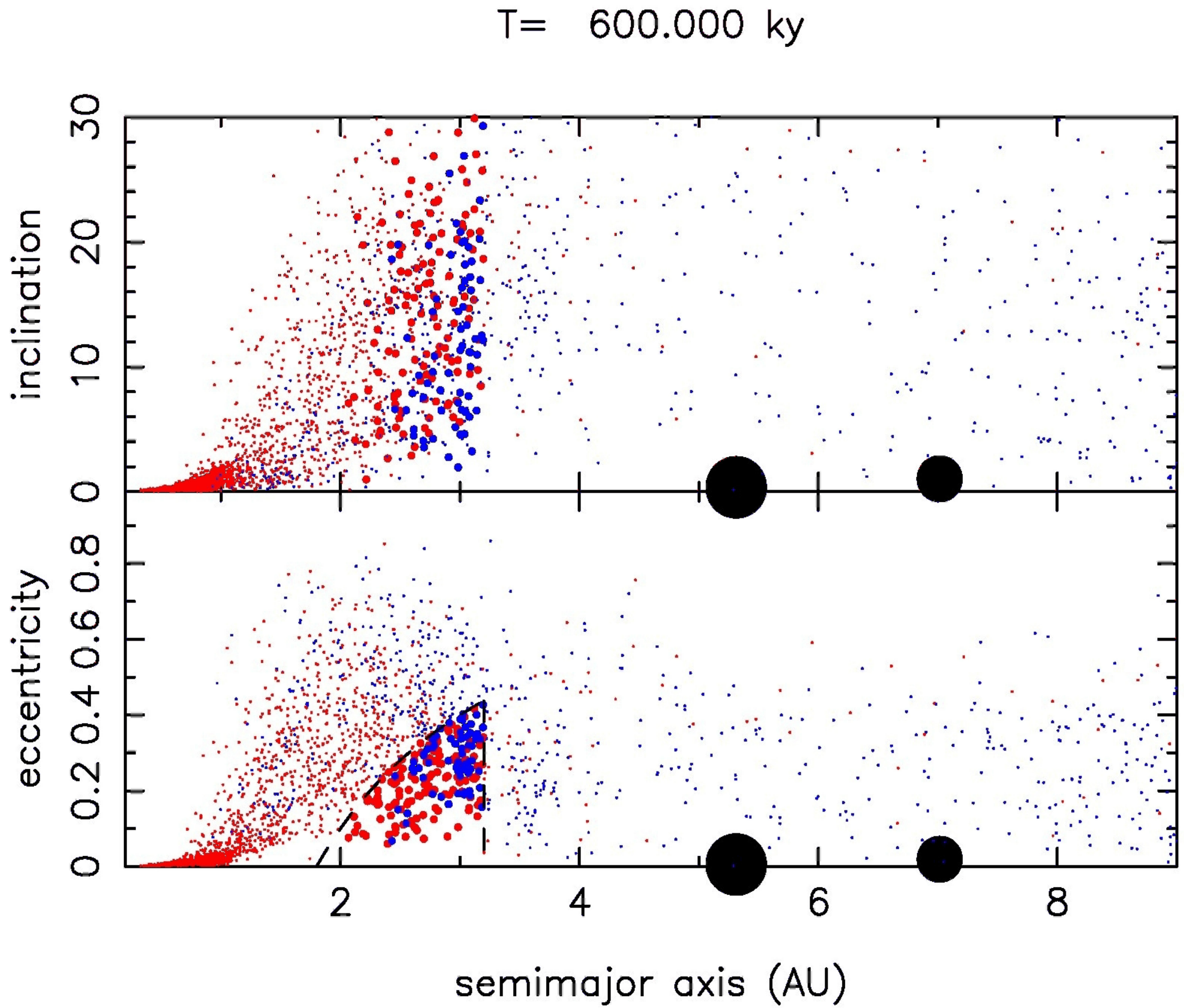
● **C-type**



Walsh et al., 2011

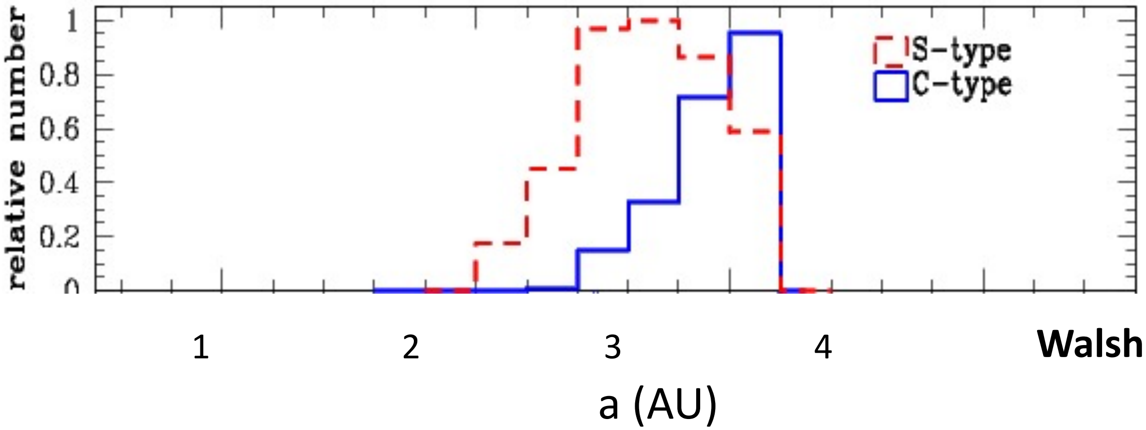
● **S-type**

● **C-type**



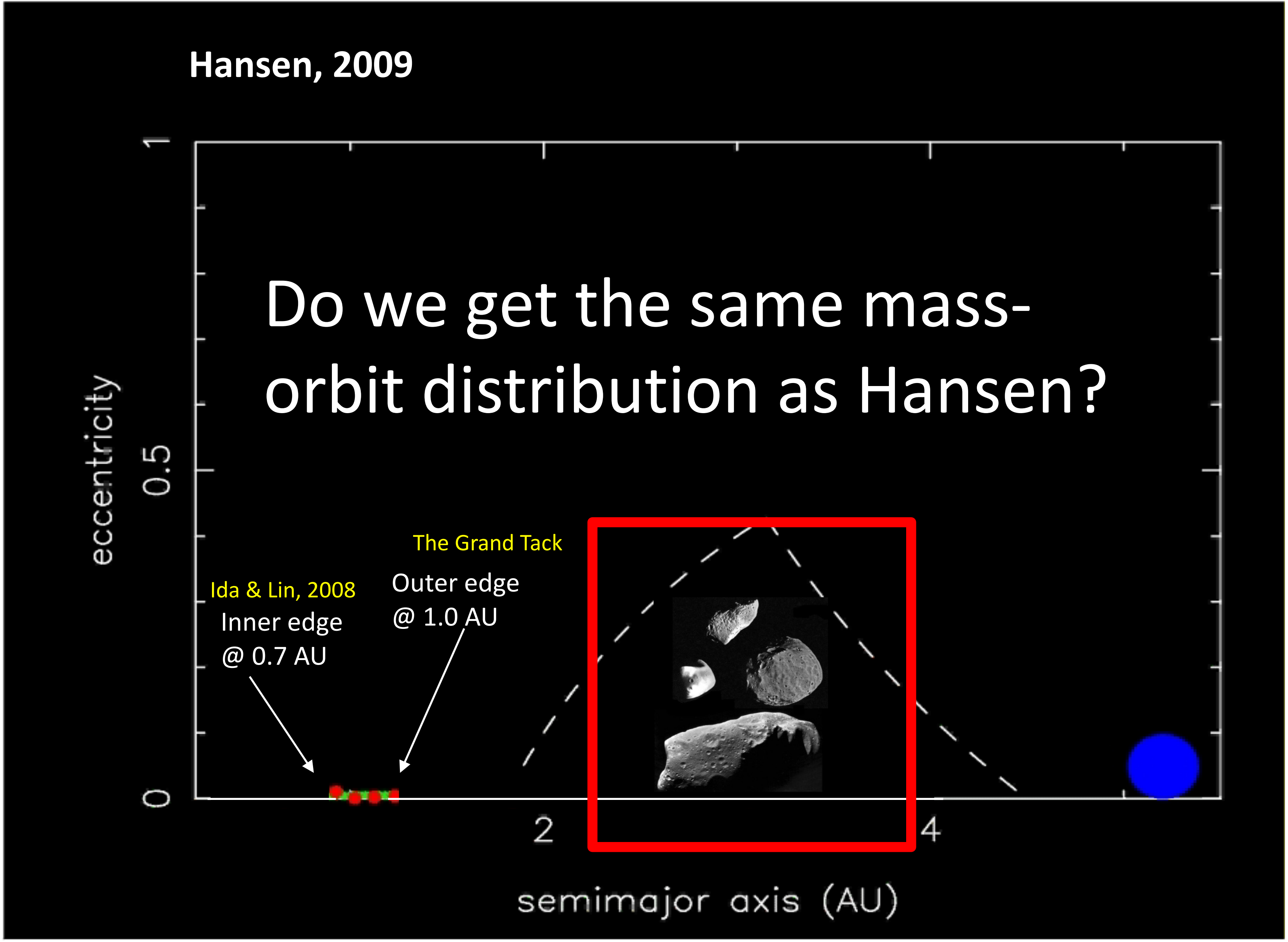
Asteroid Belt Constraint

- Relative semi-major axis distribution of inner (S-type) and outer (C-type) asteroids
- Explains for the first time, why this striking dichotomy exists



Walsh et al., 2011

From embryos to terrestrial planets



Hansen, 2009

Do we get the same mass-orbit distribution as Hansen?

Ida & Lin, 2008

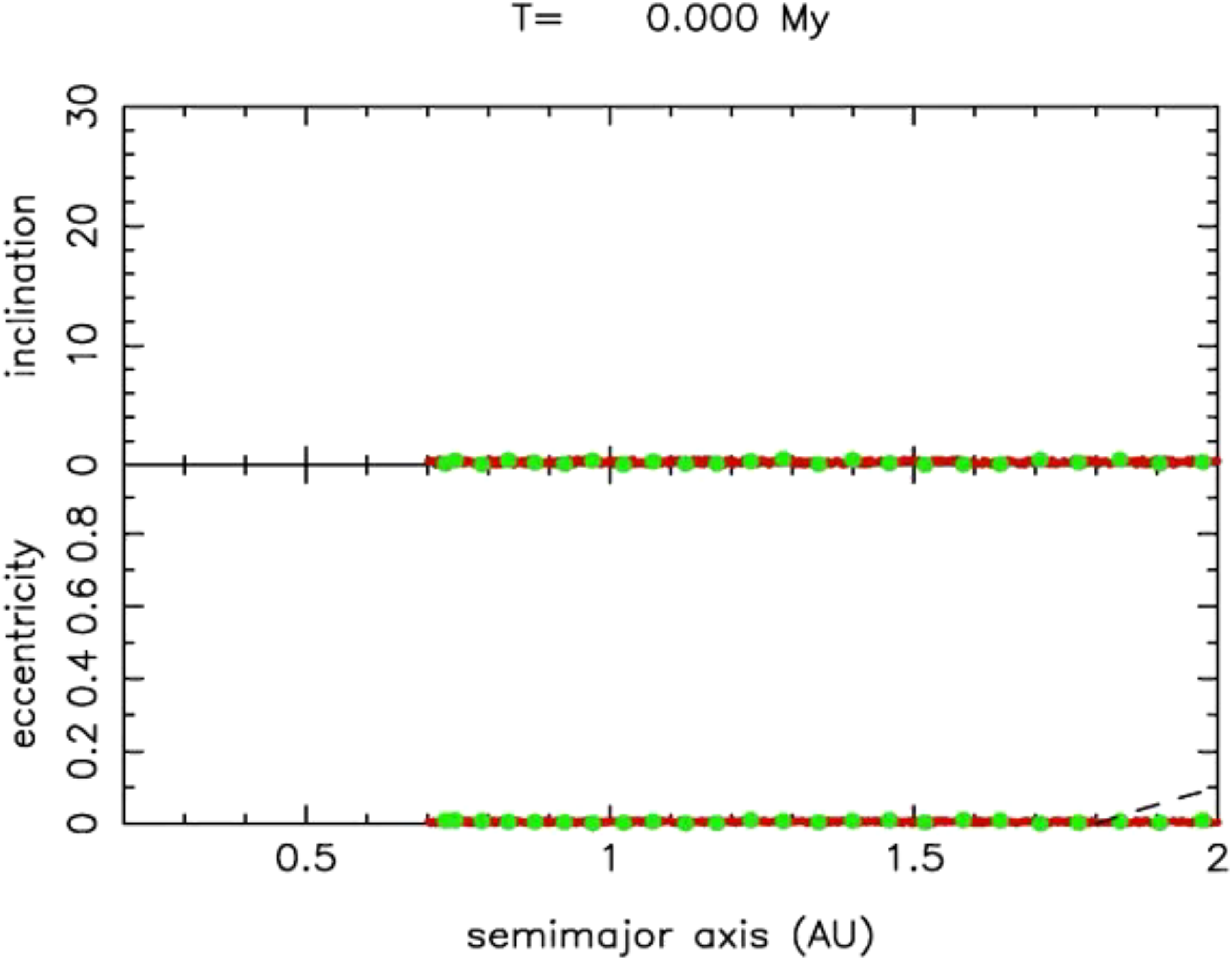
Inner edge
@ 0.7 AU

The Grand Tack

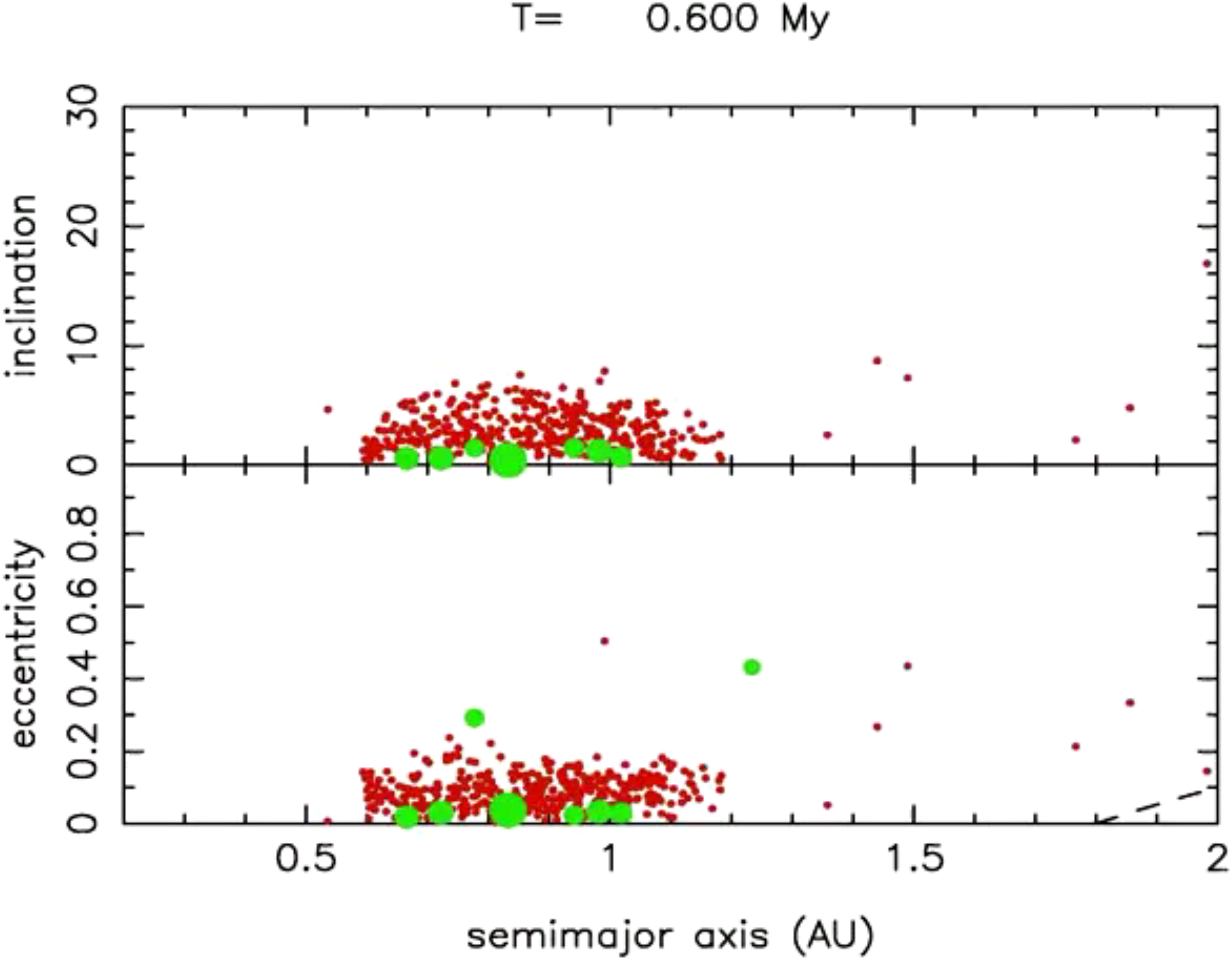
Outer edge
@ 1.0 AU

Hansen(2009)

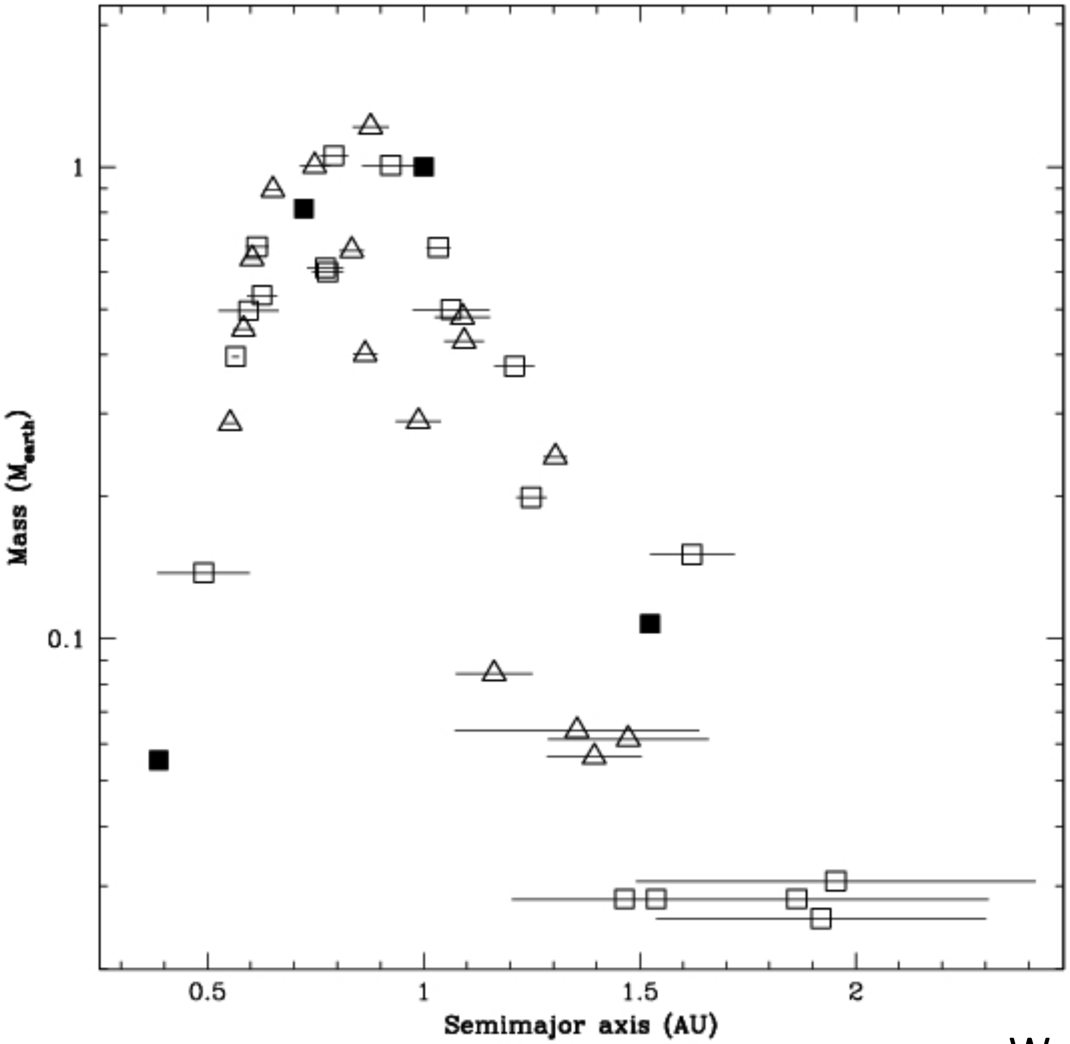
Walsh et al., 2011



Walsh et al., 2011

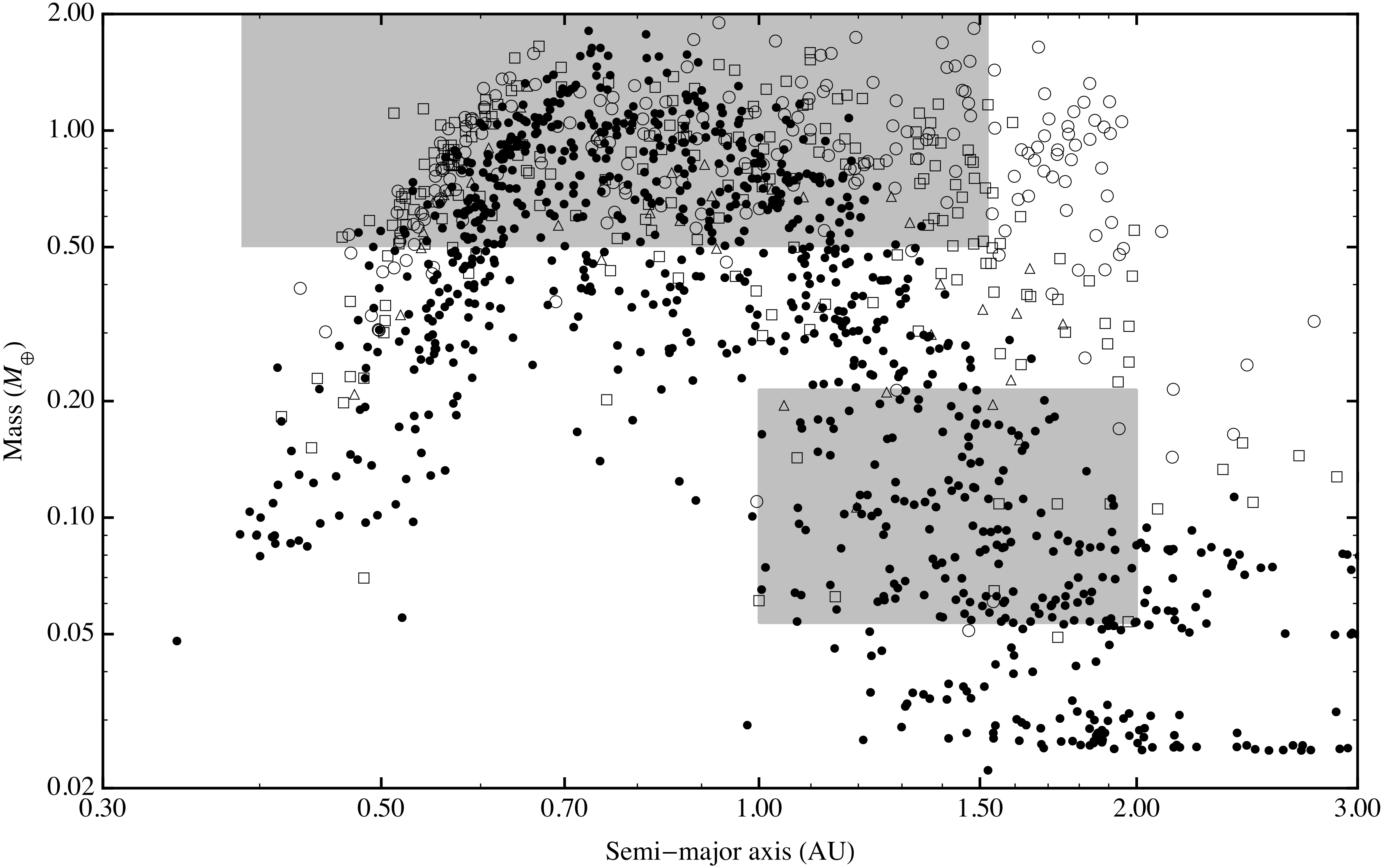


Grand Tack makes a Small Mars!

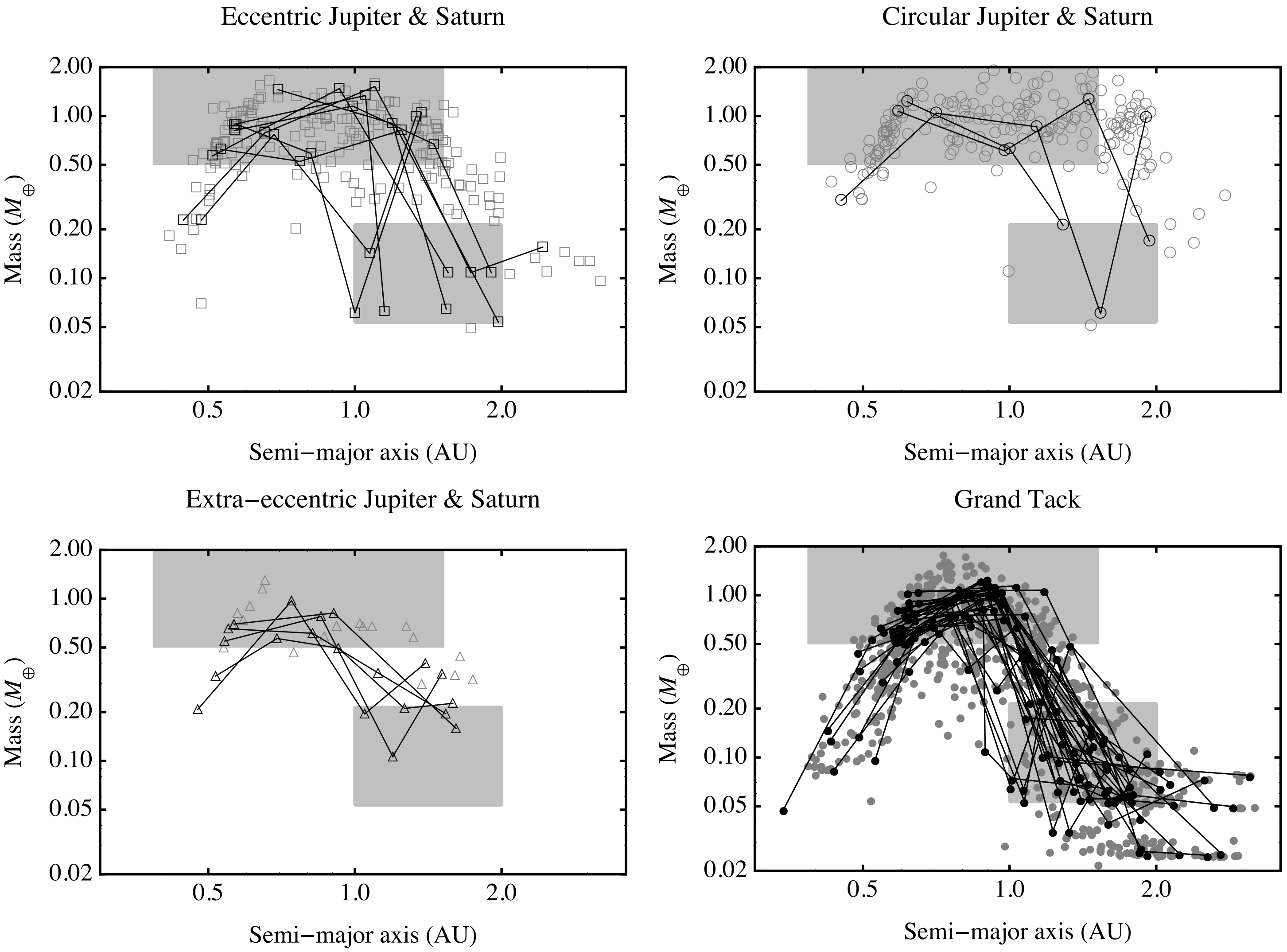


Walsh et. Al (2011)

Compare to standard models



What about those few standard models that create a small Mars?

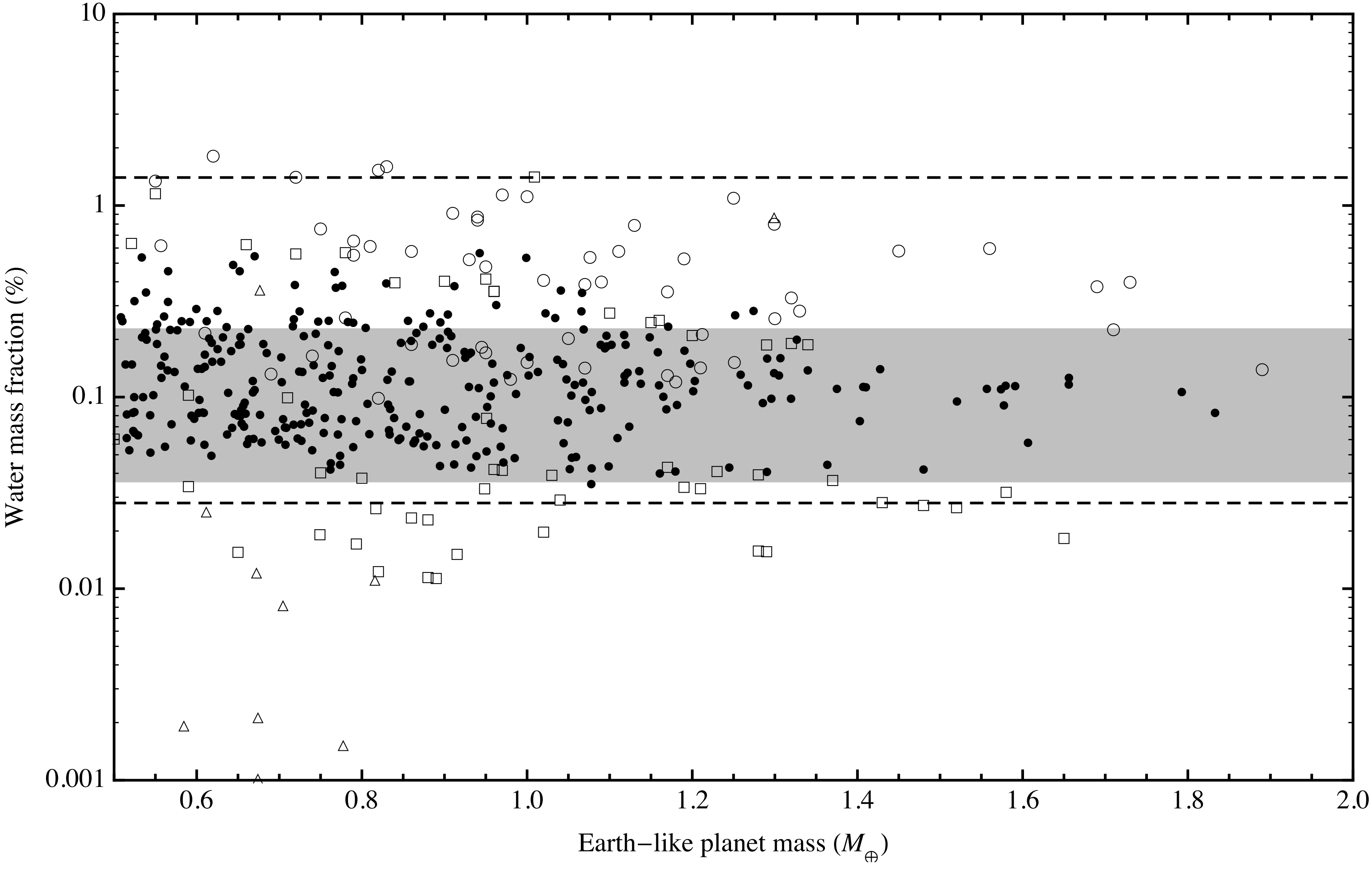

Eccentric Jupiter & Saturn

Circular Jupiter & Saturn

Extra−eccentric Jupiter & Saturn

Grand Tack

What about the water?



Step 3 Complete
Embryos to our planets

Pebble accretion can explain the Great Dichotomy in the Solar System

Pebble processes lead to a bi-modal disk like the runaway and oligarchic growth

Standard models fail to create a small Mars, but a migrating Jupiter and Saturn succeed at truncating the disk

The Nice model

Pruning Parameter Space

- Our original work was intended to represent an example from a large class of evolutionary tracks.
  - We made up or initial conditions, for example.

- There are been several attempts at fine-tuning/pruning parameter space to match other constraints or make the model more physical.

  1. Put the planets in resonances because it is the natural result of planet-disk interactions. *(Morbidelli et al. 2007)*

  2. Put plutos in disk because they were there.
     $\Longrightarrow$ new trigger *(Levison et al. 2011)*

  3. Restrict to models where ice giant encounters Jupiter *(Brasser et al. 2009)*
     - Saves the Earth and asteroid belt.

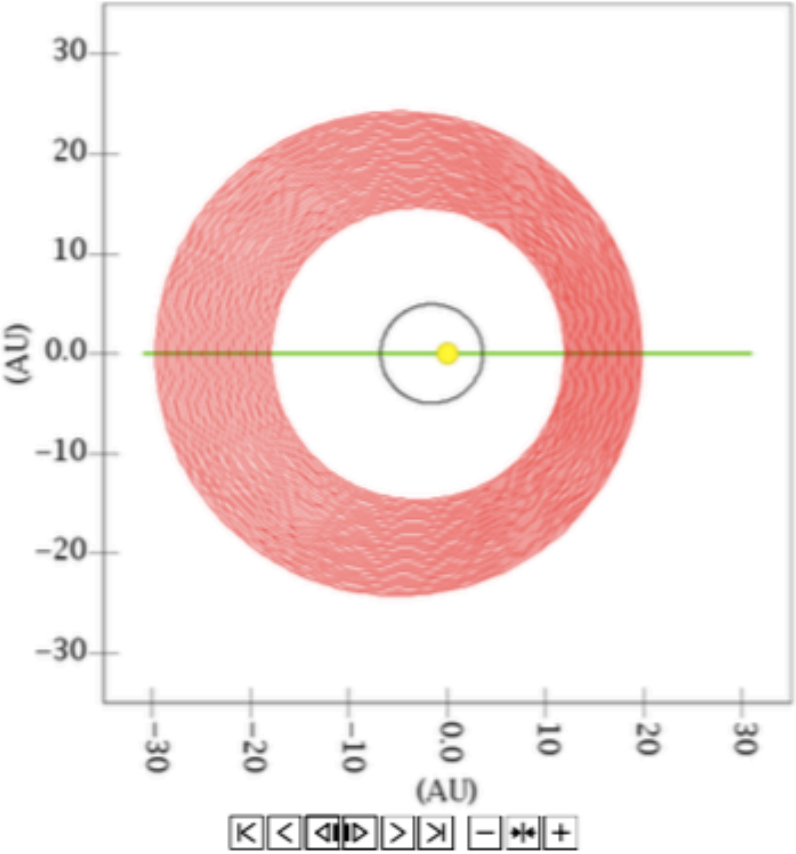
  4. Added third ice giant. *(Nesvorný & Morbidelli 2012)*
     - It just works better.
     - Except when it doesn't.

But the basic story has not changed much.

Slide taken from Hal Levison

The Effects of Viscous Stirring

- In a non-interacting disk:
  - Planet forces an asymmetry in disk.
  - This is aligned with planet's orbit $\Longrightarrow$ no torque!
- When encounters occur in disk:
  - This asymmetry is no longer aligned.
  - There is a torque on planet!
  - Planet moves.

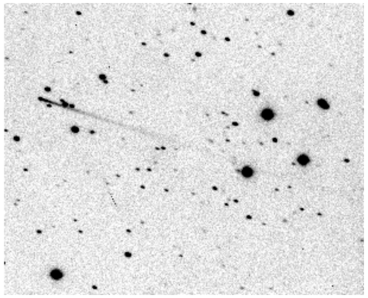


- Analogous to viscosity in the Earth-Moon system.
  - Without viscosity Earth's bulge would be below the Moon.
  - With viscosity bulge is offset $\Longrightarrow$ Moon moves out.

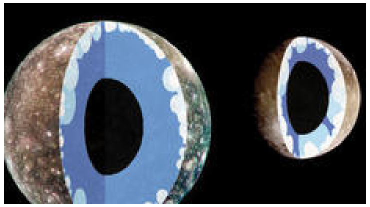
Slide taken from Hal Levison

The Nice model has done good

- Giant Planet Orbits:
  - Smooth migration should leave Jupiter and Saturn on $e=0$ orbits.
  - Scattering between the planets produce the correct orbits.
- Trojans: We get the right number and orbits.
- Late Heavy Bombardment: *(Gomes et al. 2005; Bottke et al. 2013)*
  - Reproduce duration of magnitude of impacts on Earth and Moon.



- Primitive and Active Asteroids: *(Levison et al. 2009)*
  - We reproduce the distribution and P and D-types.
- Asteroid Belt Sculpting: *(Brasser et al. 2010)*
  - Realistic smooth migration destroys the asteroid belt.
  - But, encounters between the planets saves it.
- Irregular Satellites: *(Nesvorný et al. 2006; Bottke et al. 2010)*
  - Disk particles can get trapped during planetary encounters.
- Ganymede — Callisto Dichotomy: *(Barr & Canup 2010)*
  - Ganymede suffers more impacts than Callisto $\Longrightarrow$ differentiated, while Callisto didn't.
  - Might be an issue for Saturn's small satellites *(Nimmo & Korycansky 2012)*



Slide taken from Hal Levison

What is the next step?

The Grand Tack can successfully reproduce the orbits and masses of the terrestrial planets as well as the composition and dynamics of the asteroid belt

The Nice model reproduces the orbital features of the giant planets as well as the dynamical and compositional features of many of the small body populations

What is the next step?

Masses and orbits are just first order constraints

It’s time to consider geology

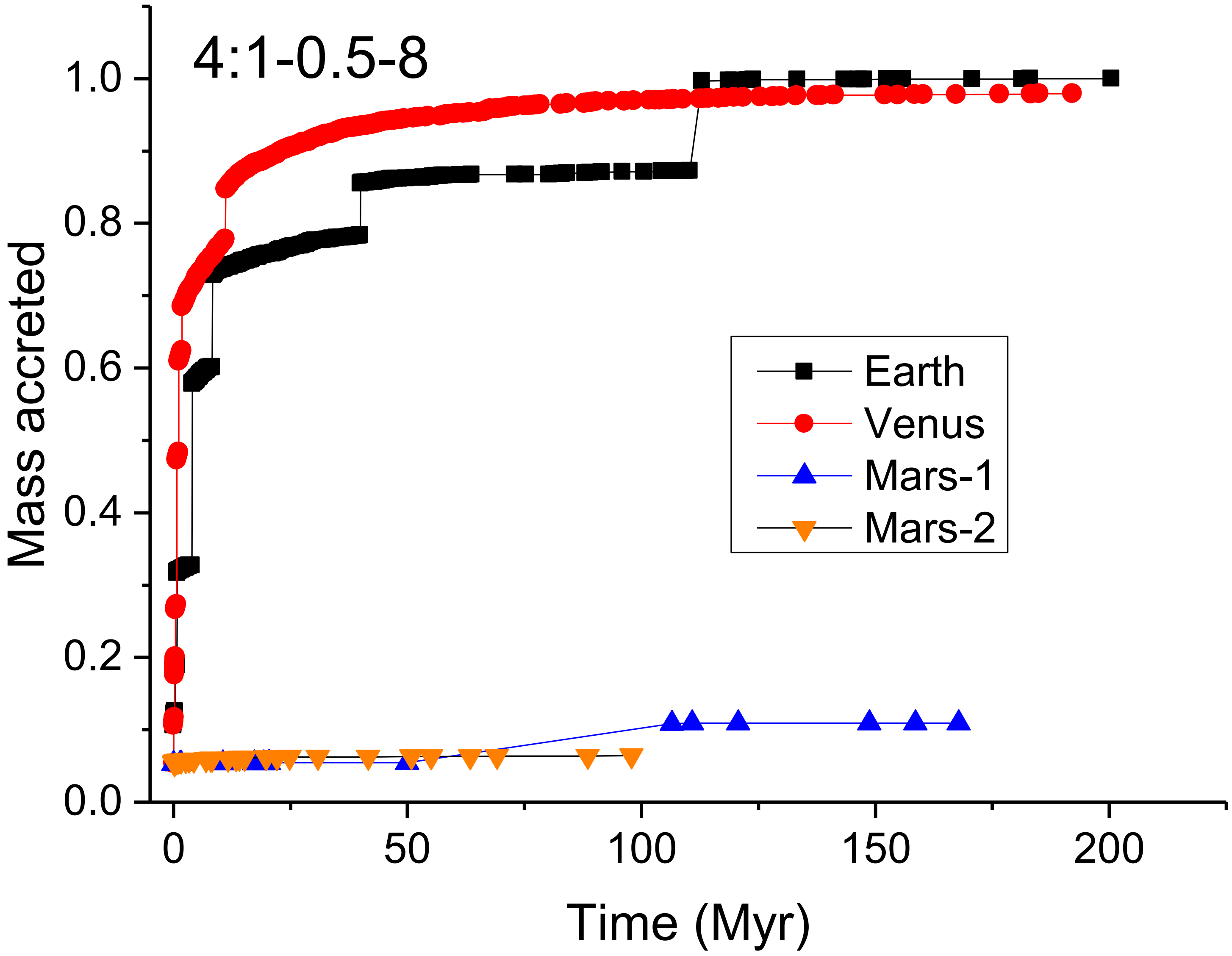
How can what we know about the Earth’s geology as well as the geology of meteorites and other bodies constrain Solar System formation

Combining planetary accretion with core-mantle differentiation

We have combined N-body accretion simulations with a multistage core-mantle differentiation model based on the concentrations of Fe, Si, Ni, Co, Ta, Nb, V, Cr and H_2O in Earth's mantle (Rubie et al. 2015, Icarus).

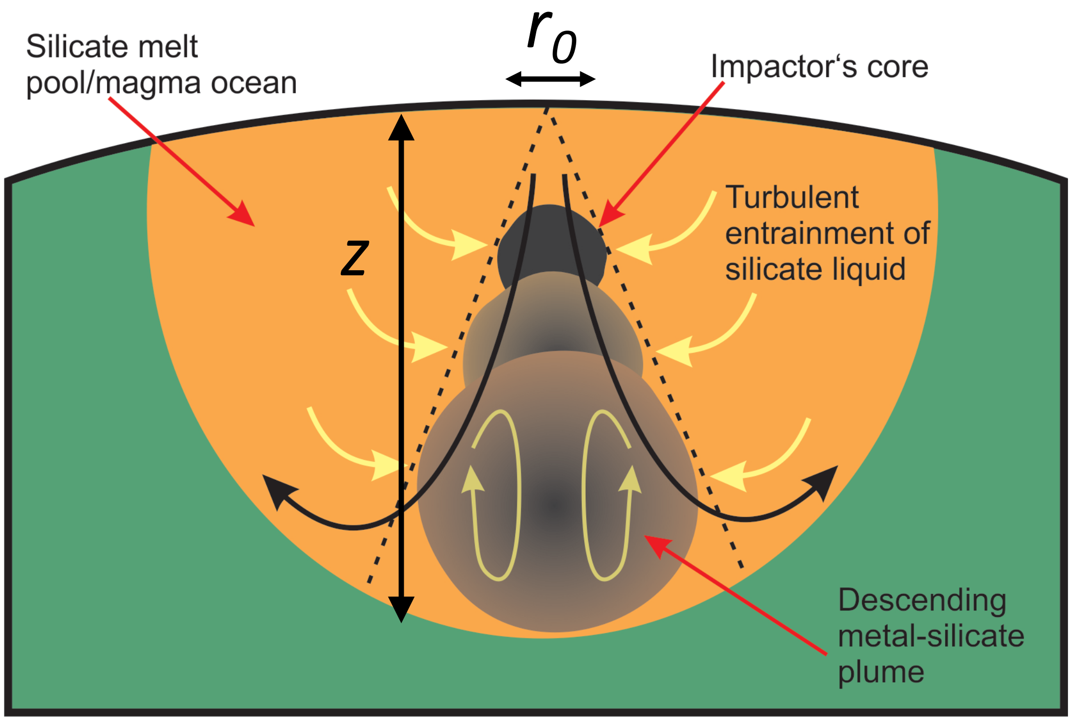
Each accretional impact between differentiated bodies is treated as a core-forming event that involves metal-silicate equilibration at high pressure in a magma ocean

Accretion histories



Proportion of an target’s mantle/magma ocean that equilibrates with the impactor's core

(Hydrodynamic model of Deguen et al., 2011, EPSL)



$$\phi = \left(\frac{r_0}{r}\right)^3 = \left(1 + \frac{\alpha z}{r_0}\right)^{-3}$$

where Φ is the volume fraction of metal in the metal-silicate mixture

Fraction of equilibrating mantle:

- 0.1-1.0% for planetesimal impacts
- 3-11% for embryo impacts

(Consistent with Kendall and Melosh, LPSC 2012)

Composition - mass balance approach to core formation modeling

(Rubie et al., 2011, *EPSL* **301**, 31-42)

1) Define the bulk composition of accreting material – solar system (CI) ratios of non-volatile elements and variable oxygen contents. A spectrum of oxidation states between:

Highly reduced (oxygen-poor):	99.9% of Fe present as metal
Fully oxidized (oxygen-rich):	No metal

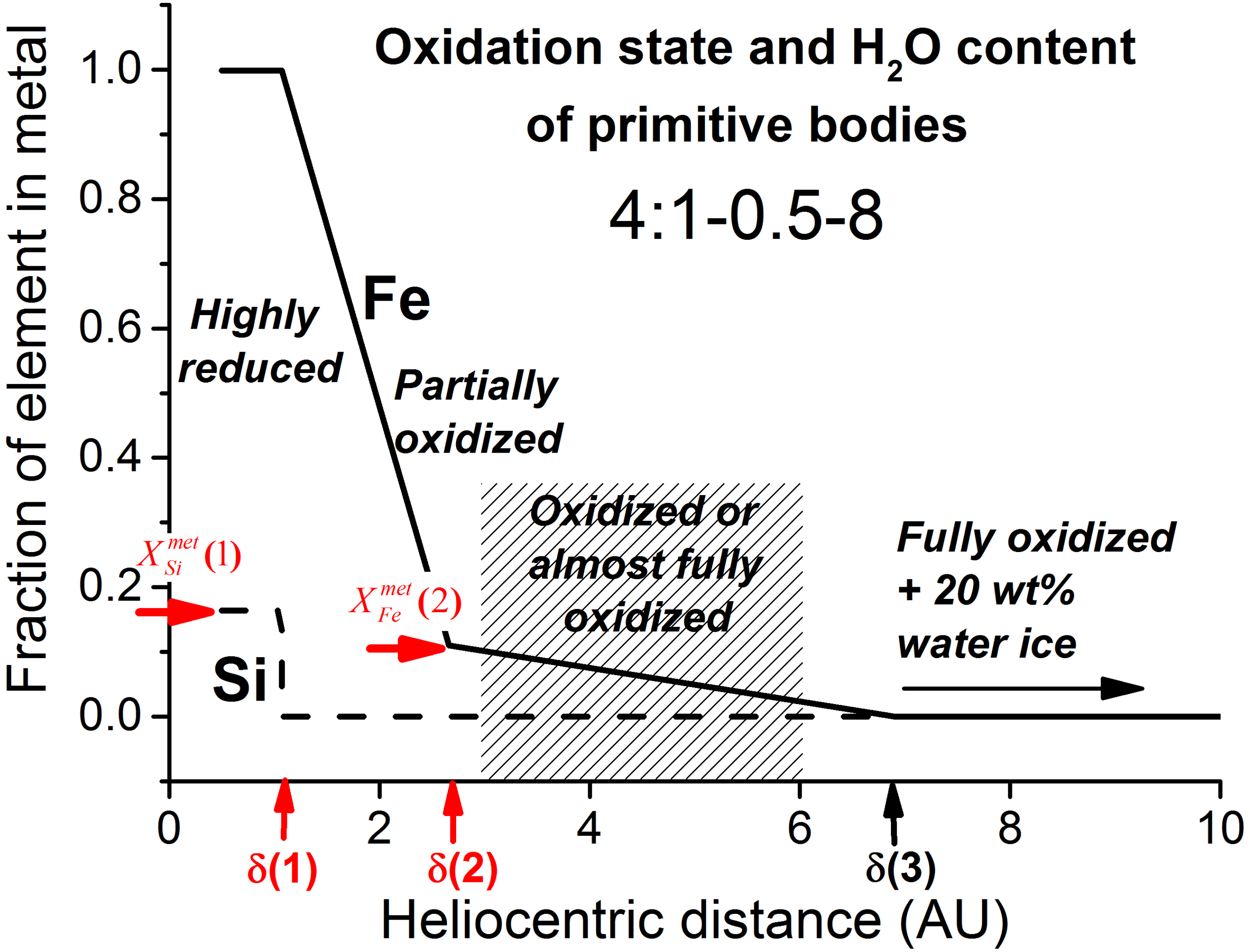
2) Determine equilibrated compositions of co-existing silicate and metal liquids at high *P-T*:

$$[(FeO)_x\ (NiO)_y\ (SiO_2)_z\ (Mg_u\ Al_m\ Ca_n)O] + [Fe_a\ Ni_b\ O_c\ Si_d]$$

silicate liquid ***metal liquid***

using 4 mass balance equations together with 3 models for the metal-silicate partitioning of Si, Ni and FeO.

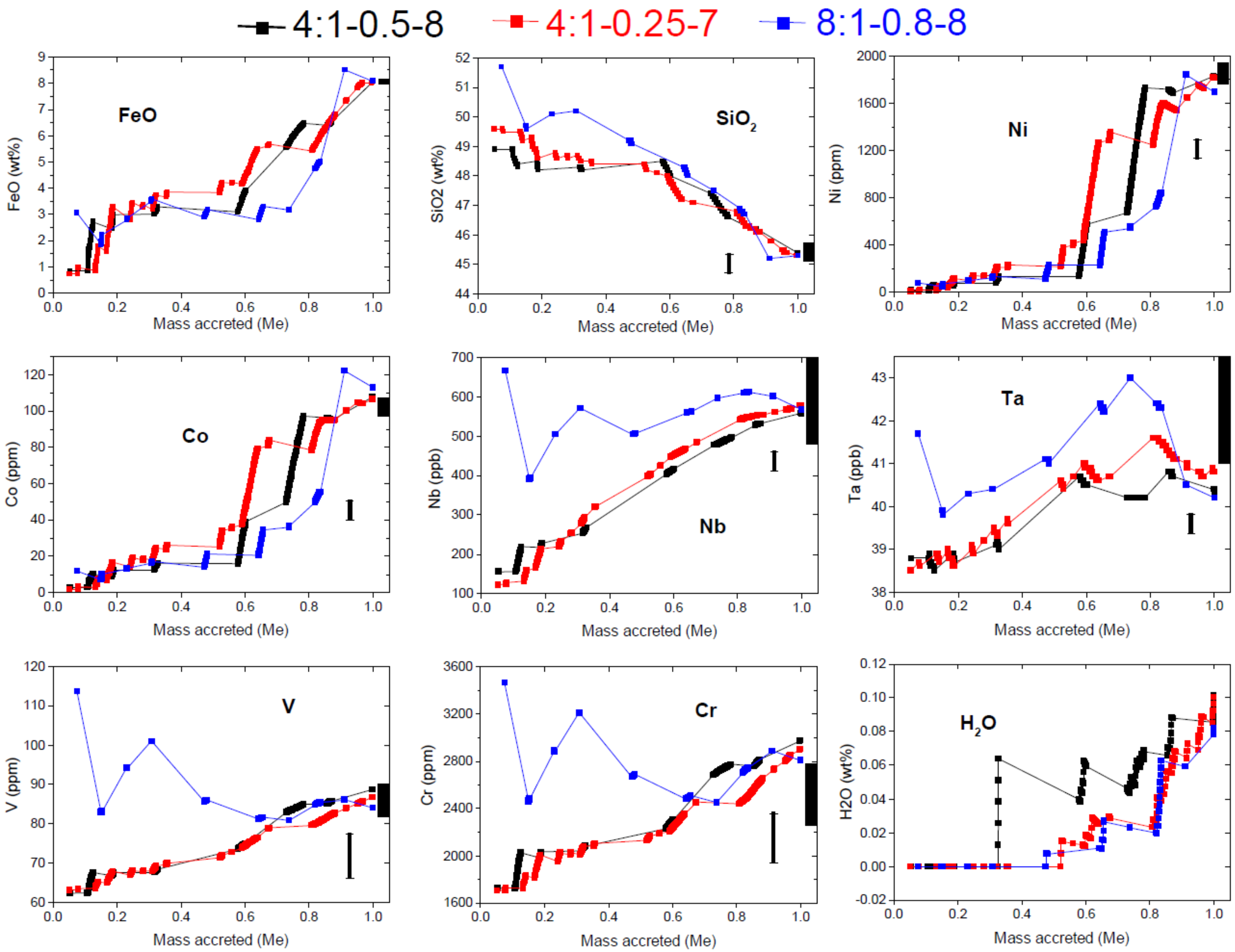
Compositions of primitive bodies in the proto-planetary disk



5 Fitting parameters in least squares regressions:

- Effective pressure of metal-silicate equilibration as a fraction of CMB pressure (increases as Earth grows) ~ $0.7 \times P_{\mathrm{CMB}}$
- Compositions (e.g. oxygen contents) of proto-Earth and impactors (4 fitting parameters)

Evolution of element concentrations in Earth’s mantle



Final core composition: 82 wt% Fe, 5 wt% Ni, 9 wt% Si, 3 wt%O, 48 ppm H