News and Reminders

Homework 6 (last one!) - posted, due Dec. 2

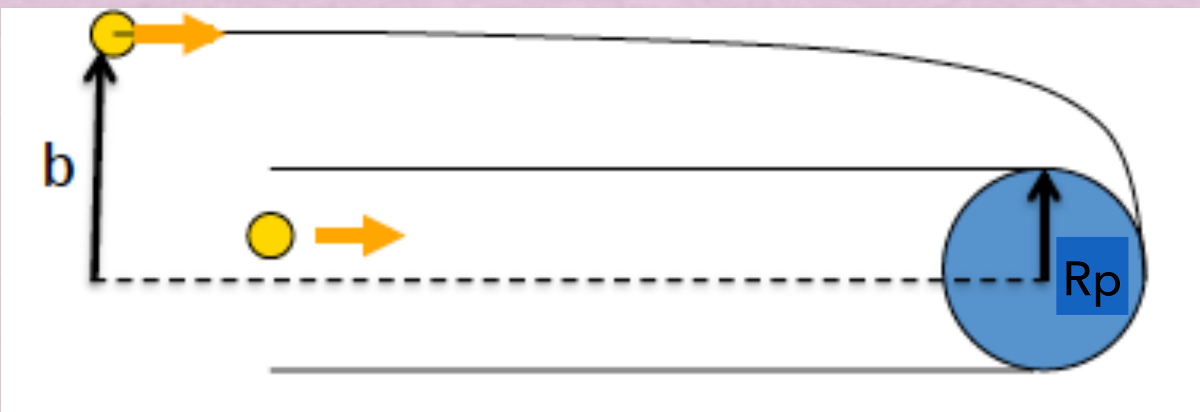
End of semester proposal due dates:

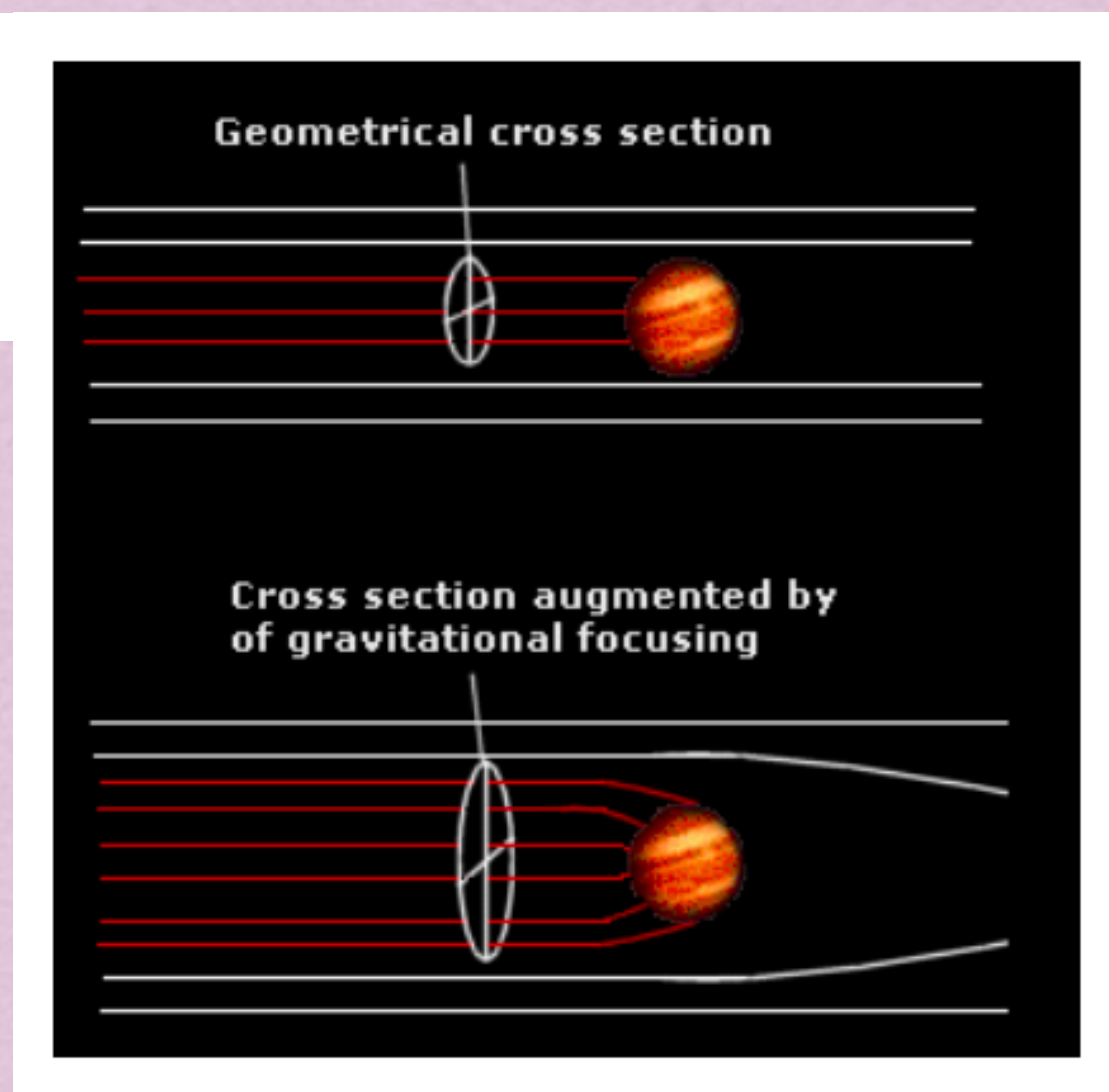
- Proposal due: Monday, Dec. 2
- Proposal review: Wednesday, Dec. 4

Bonus topics: email me your suggestions by Wednesday (Nov. 27)

Download Wolfram CDF player in preparation for Monday's guest lecture:
http://www.wolfram.com/cdf-player/

Gravitational Focusing





Without gravitational focusing:

$\Gamma = \pi \ R_p^2$

With gravitational focusing:

$\Gamma = \pi \ b^2 = \pi \, (R_c^2 + 4R_cGm/v^2)$

Runaway and Oligarchic Growth

When $v \ll v_e$, embryos accrete planetesimals very quickly -> **runaway growth**

In a group of embryos, the larger ones can excite nearby planetesimals to higher velocities; the smaller ones, less so, so they grow faster -> **oligarchic growth**.
This means that growth eventually slows for all embryos, once they get large and massive enough.

Embryo can only accrete planetesimals from nearby, because those arriving from a wider range of heliocentric distances have too high v.

When planetary embryo has consumed all planetesimals within gravitational reach, runaway growth stops -> **isolation mass.**

For minimum mass solar nebula:
M_{iso} = 6 Moon masses near Earth's orbit (0.07 Earth masses)
M_{iso} = 8 Earth masses near Jupiter's orbit

So isolation mass is higher in outer solar system.

Isolation mass:

$$M_i = 1.6 \times 10^{25} \left(r_{AU}^2 \sigma_p\right)^{3/2} \sqrt{\left(\frac{M_\odot}{M_*}\right)}$$

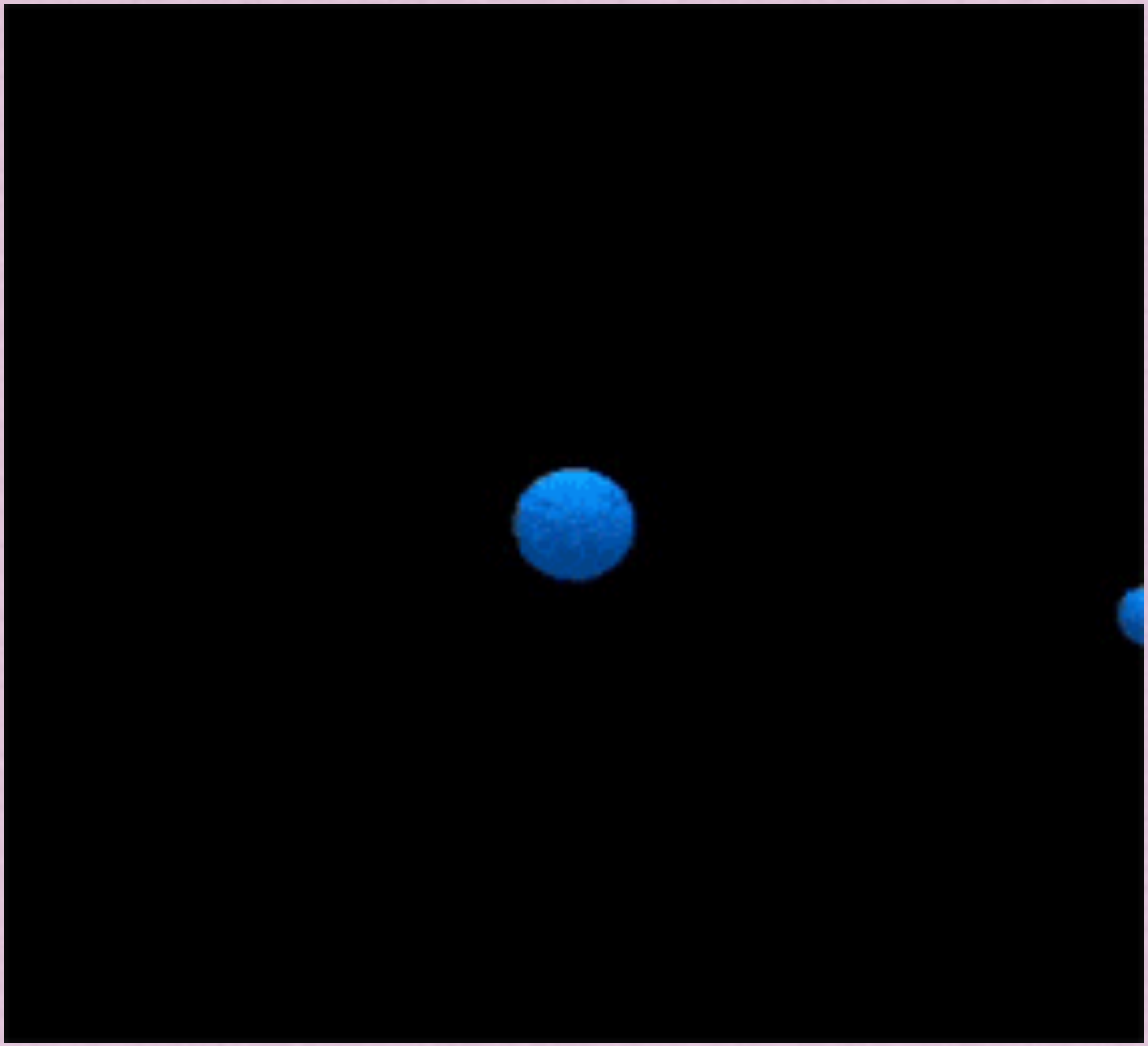
How do the planetary embryos grow further?

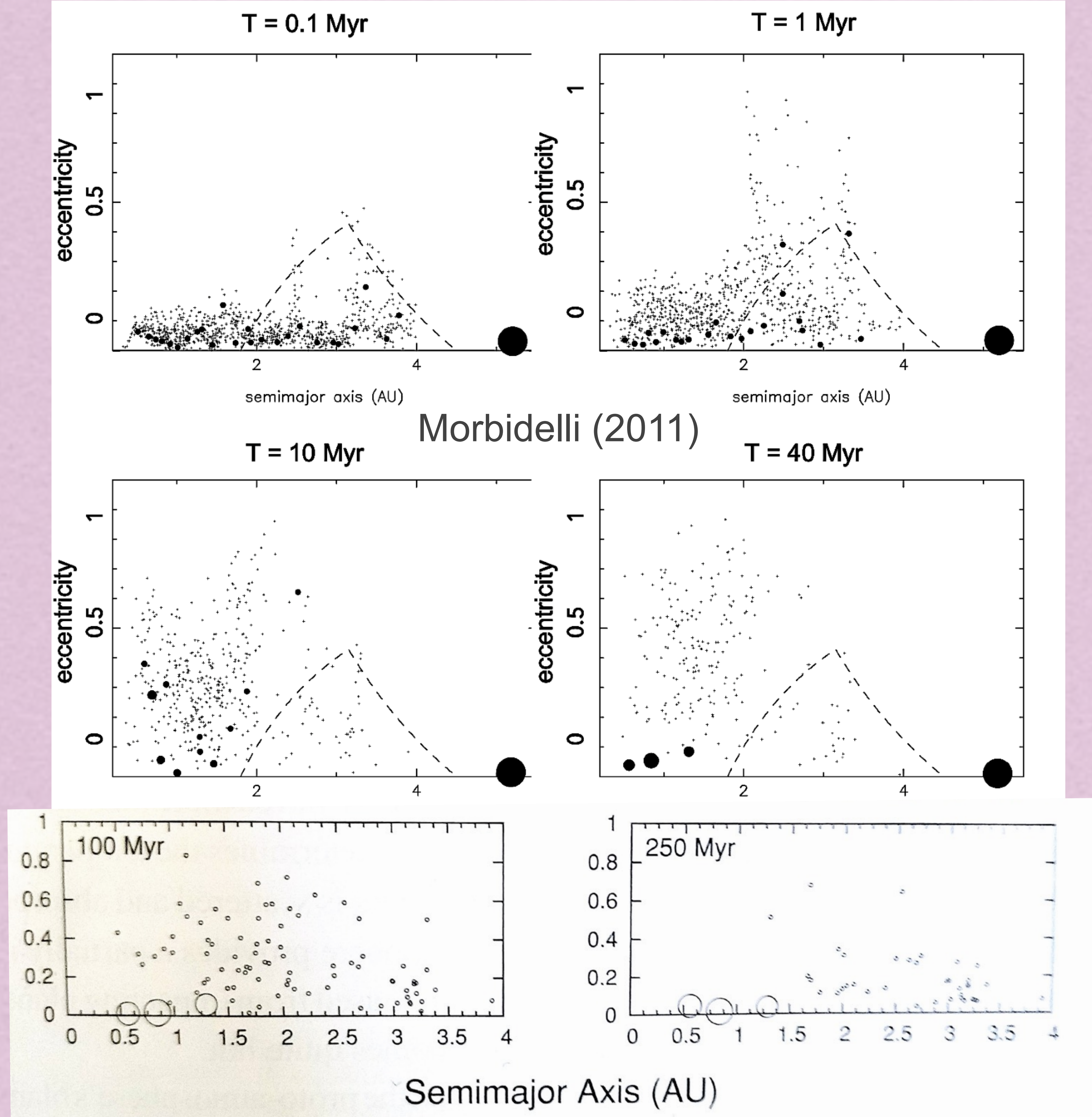
- scattering between planetesimals
- perturbations of planetesimals by nearby still-accreting embryos
- gas drag
- radial motion of the embryo can take it to other zones with planetesimals

Planetesimal accretion is inefficient!

Formation of the terrestrial planets

- oligarchic growth is self-limiting + not much gas left = embryos are orbiting at regular intervals in semi-major axis
- gravitational interactions excite velocities, which reduces the collision cross-section
- growth continues via close encounters and collisions, but slower than the runaway growth phase



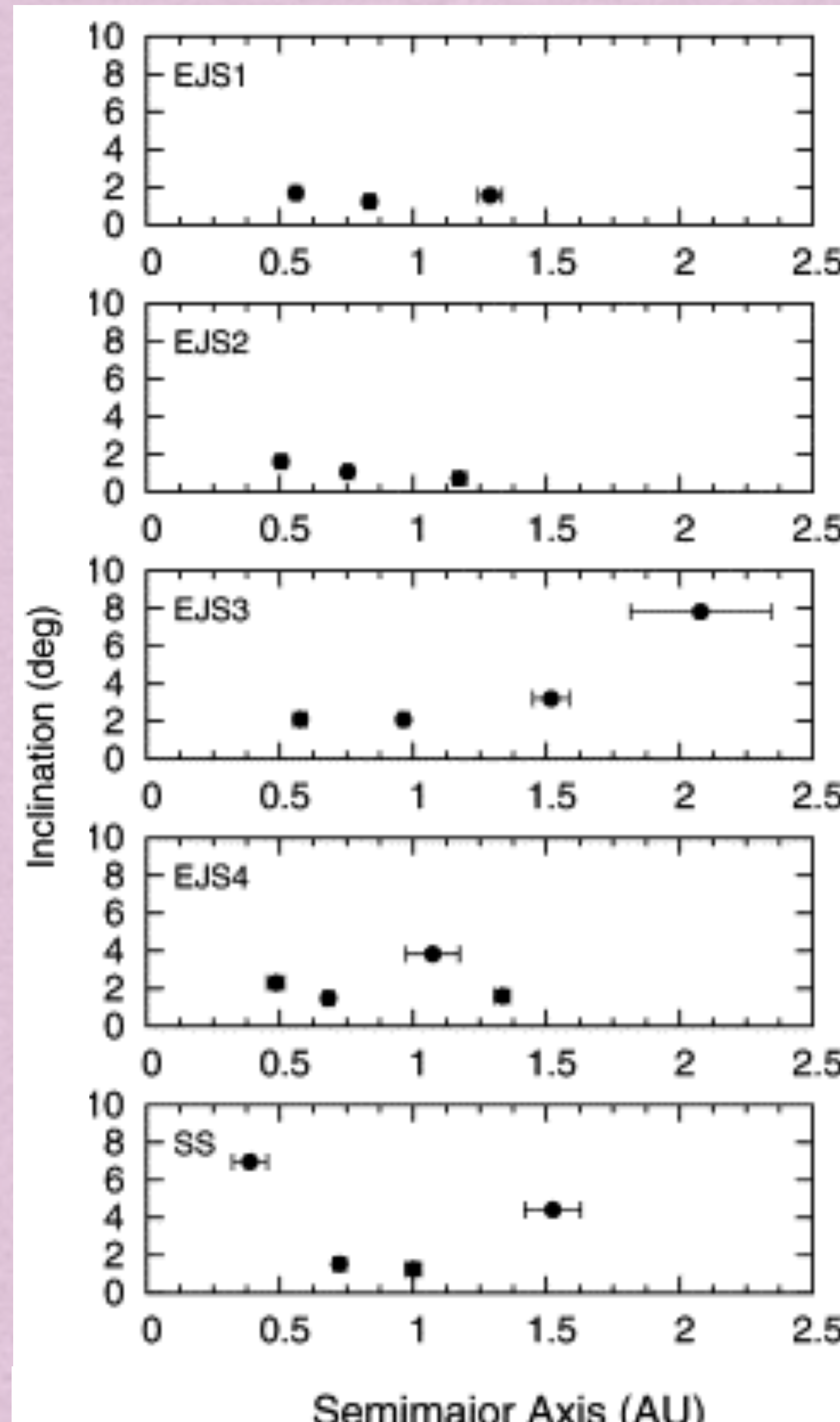

T = 0.1 Myr
T = 1 Myr
eccentricity
semimajor axis (AU)
Morbidelli (2011)
T = 10 Myr
T = 40 Myr
100 Myr
250 Myr
Semimajor Axis (AU)

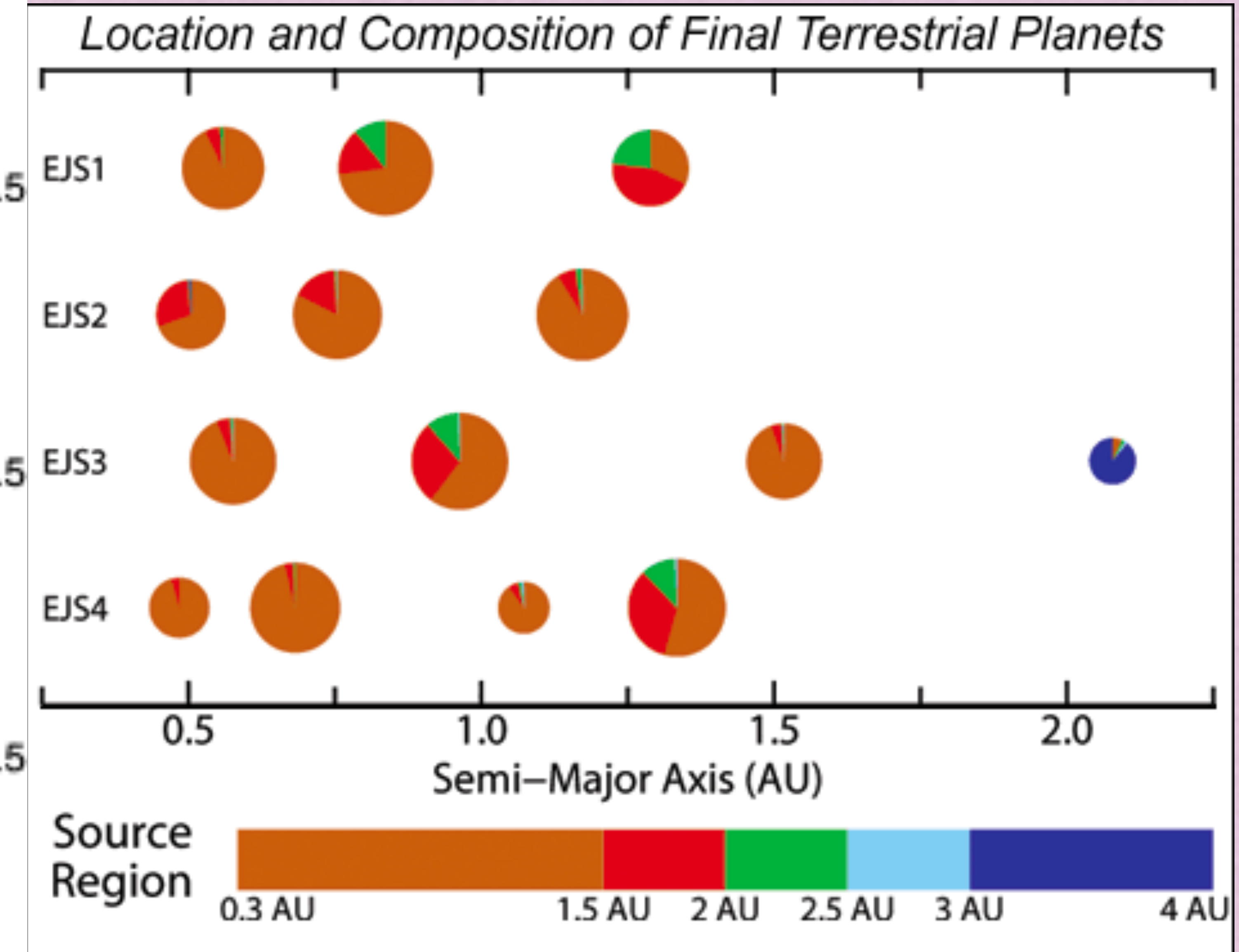
Formation of the terrestrial planets

- random walks in semi-major axis -> mixing of material through the terrestrial planet region
  - but some correlations with heliocentric distance still remain

- debris generated from the collisions acts as new planetesimals
  - before these are accreted, they form a residual planetesimal disk that damps eccentricities and inclinations through dynamical friction
    - the more massive the residual planetesimal population, the stronger the dynamical friction effect is

Formation of the terrestrial planets



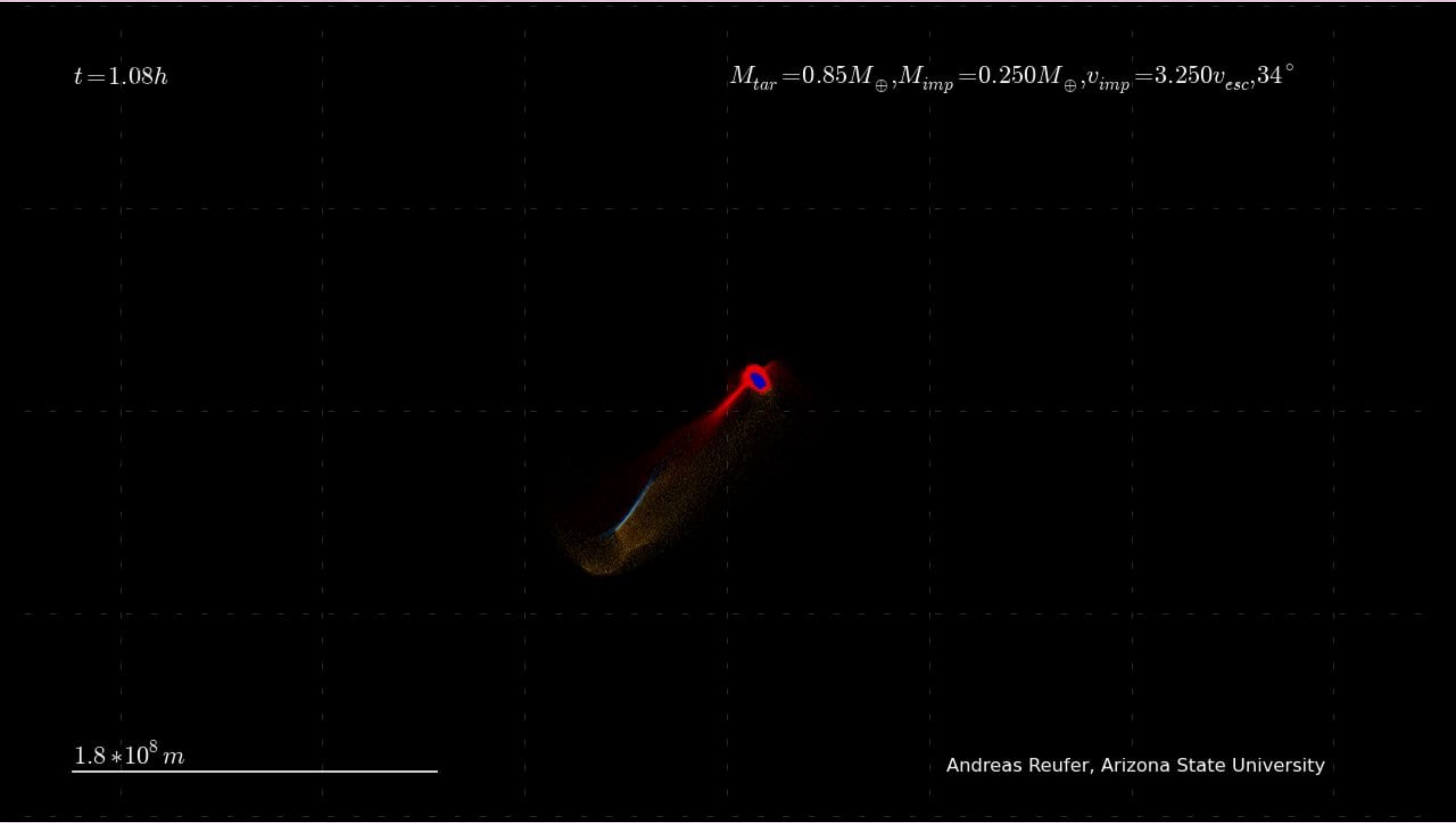


(From O'Brien *et al.* (2006), *Icarus*, v. 184, p. 39-58.

- initial disks are very similar for the four simulations
- differences in the four models come from random variations in the accretion dynamics

What about Mercury?

- if Mercury can avoid being accreted in the embryo -> protoplanet phase, then a more massive impactor could have collided with proto-Mercury, dispersing its mantle
  - Venus accretes the mantle and Mercury is left with the structure we know today



Formation of the terrestrial planets

Heating and Differentiation

Heat sources:

- impacting planetesimals supply both kinetic and potential energy
- potential energy released from the planet contracting under pressure
- radioactive decay

Heat loss:

- radiation to space from the surface or the atmosphere (though heat in the interior can be transported to the surface by convection or conduction).

If planet accretes gradually, it doesn’t heat up very much before the heat is lost to space. But the terrestrial planets obtained their mass a lot at a time through impacts with large planetesimals, so no problem right?
Except that the impactor can also raise buried heat to the surface where it can radiate away.

<u>Solution:</u> the ejecta from the impact settles and insulates the surface, keeping the heat in before it can radiate away.
Temperature exceeds 1600 K, and most materials melt. Heavier materials (e.g. iron) sink through the lighter materials.
Gravitational potential energy is released in the planet’s deep interior from this process, heating the planet throughout sufficiently to allow differentiation.

Formation of the terrestrial planets

Accumulation and Loss of Atmospheres

Terrestrial planets do acquire H and He atmospheres, but lose them early due to the relatively weak gravitational field of the planets.

Heavier gases may also escape through impacts that blow off a portion of the atmosphere (impact erosion).

The terrestrial planets' atmospheres are secondary atmospheres.

These were outgassed from the accreted solids through volcanic eruptions, early in their lives when they were still warm.

Formation of the Giant Planets

Needs to be fast! Gas disk disperses within 10 Myr or less.

Sun's atmosphere has <2% elements heavier than Helium
Giant planets' atmospheres have between 5 and 300 x more heavy elements than the Sun!

For Jupiter and Saturn, D/H ratio is similar to that of the interstellar medium.

For Uranus and Neptune, D/H ratio is higher than that of the interstellar medium.

-> can be explained if not all D came from the solar nebula, but also from icy reservoir in the outer SS

Formation of the Giant Planets

Disk Instability

Pros:

- Fast! Happens in < 1 Myr

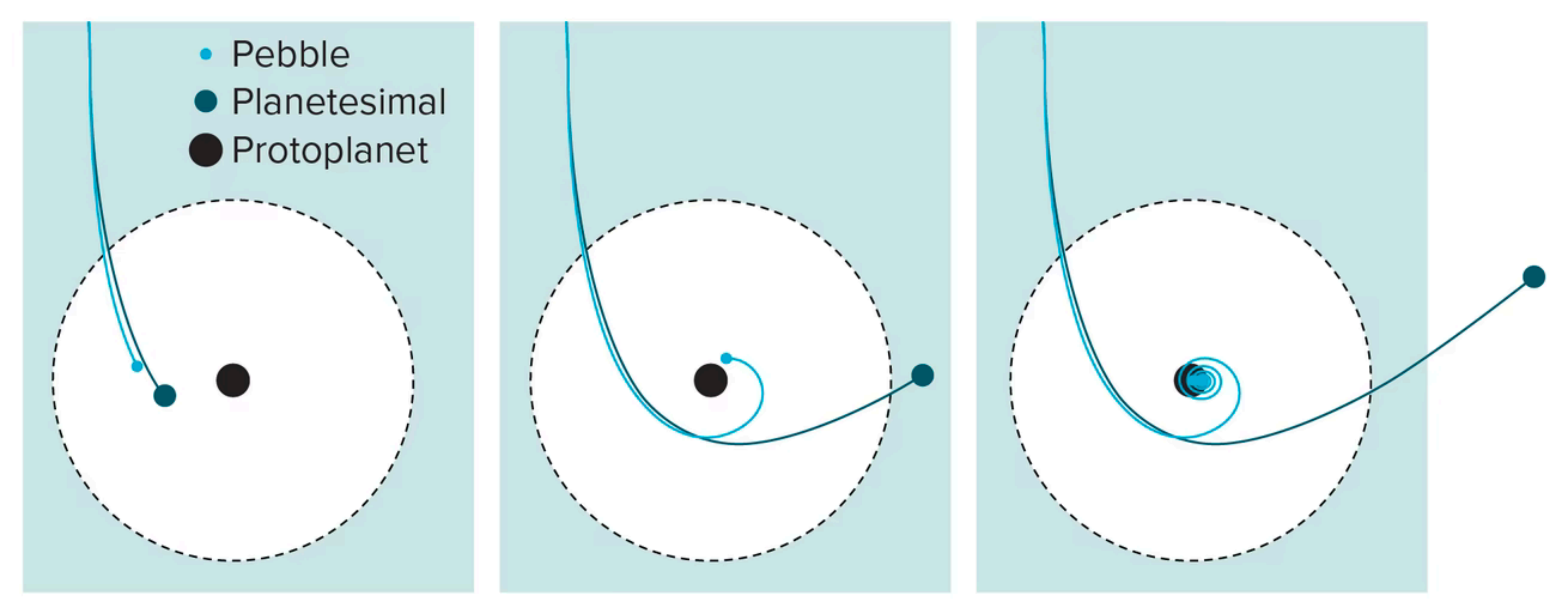
Cons:

- The gravitational instabilities lead to density waves which flatten the disk and redistribute the mass, making it more stable rather than clumpy.
  So need very specific disk properties and/or very fast accretion.

- Can't explain heavy metal enhancement
  - But, heavy metals can come from later accretion of planetesimals and pebbles.

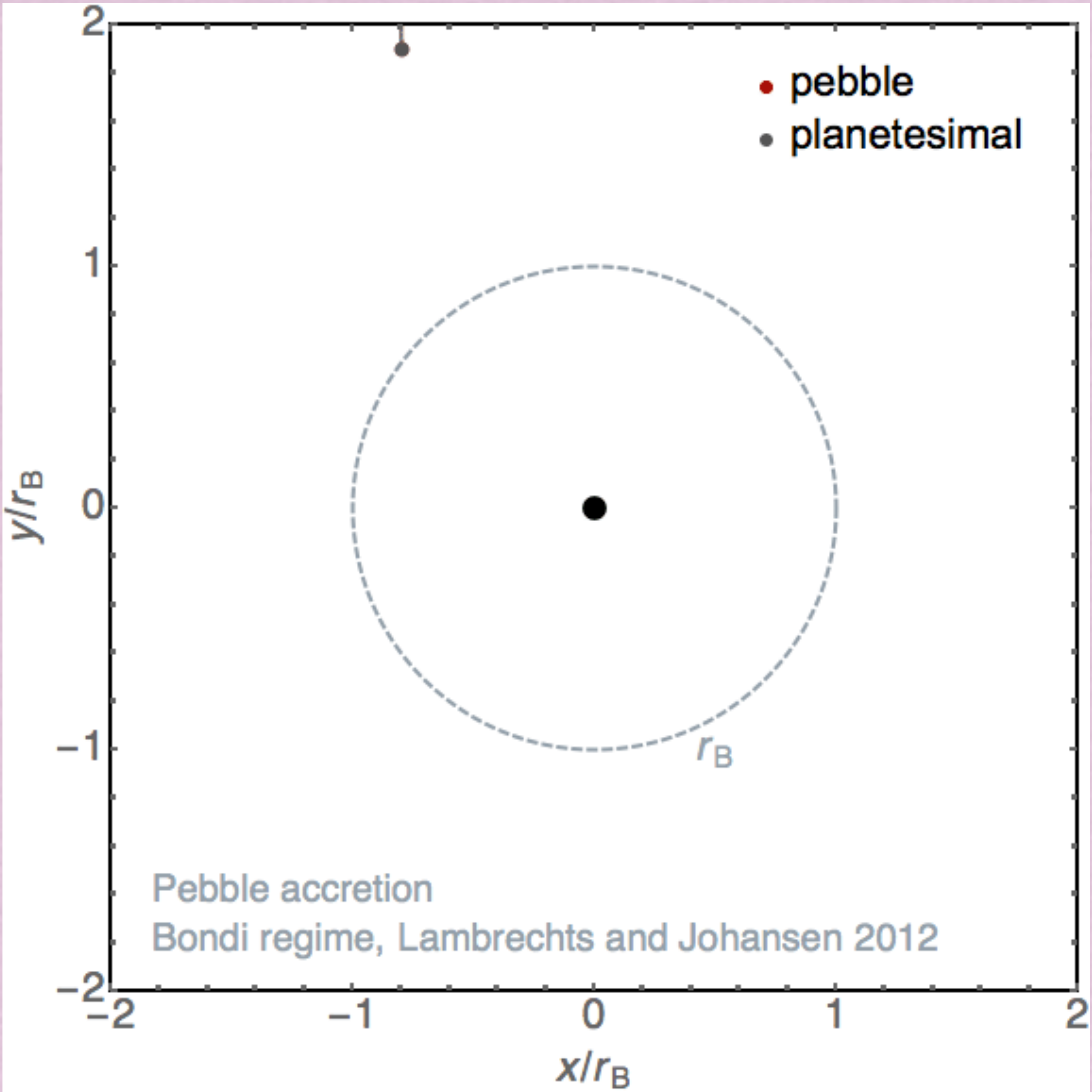
This could work at very large distances from the star where Keplerian shear is small (tens of AU)

Pebble Accretion



Credit:M. Lambrechts and A. Johansen / L. Modica / Knowable

Pebble Accretion



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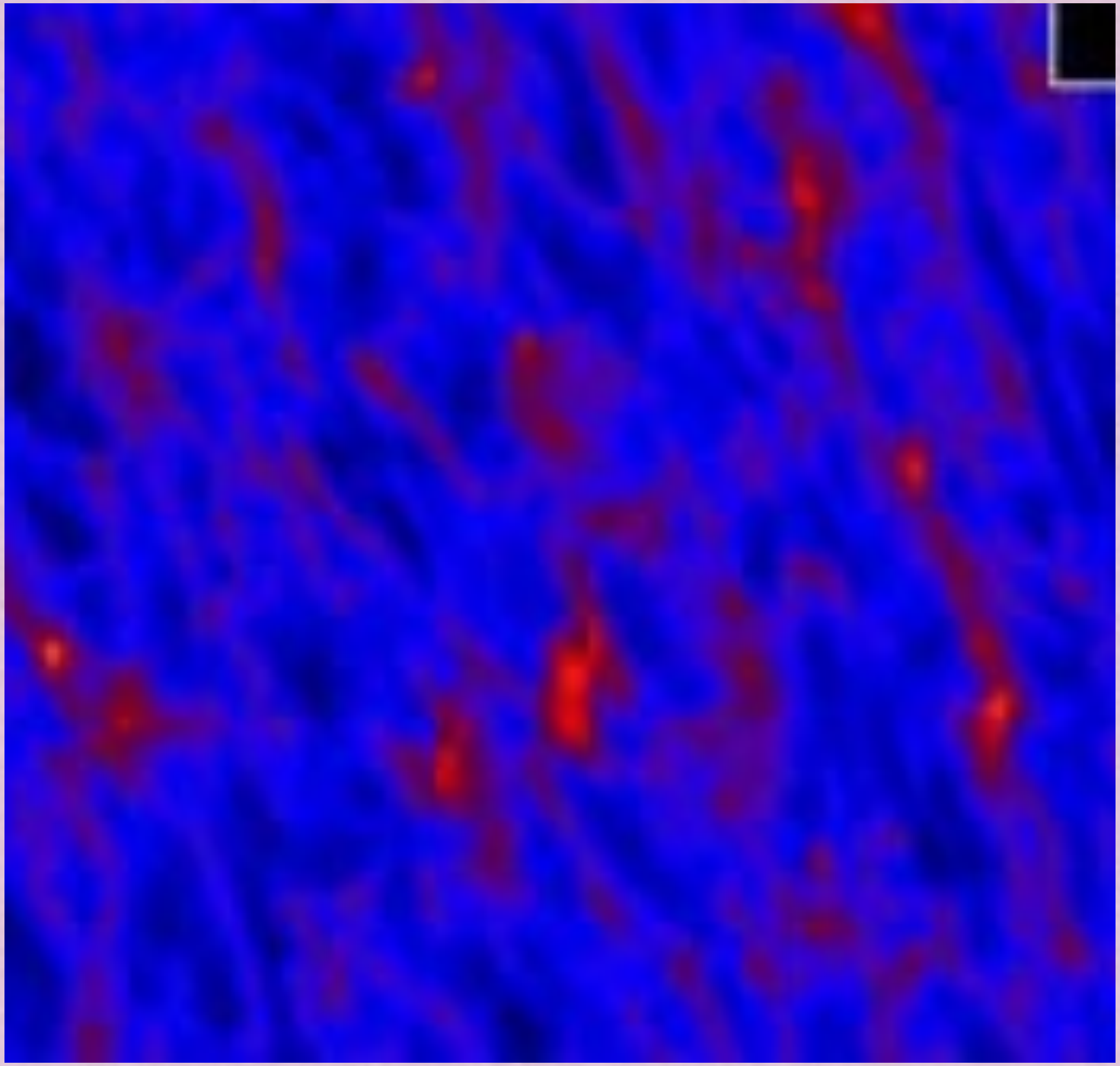

What happens to the remaining material?

- In outer solar system, remaining solids are scattered to Oort cloud or ejected by interactions with the giant planets

- In inner solar system, terrestrial planets did not have sufficient mass to eject material, so likely accreted it all

Planet Formation Summary