High-resolution simulations of the final assembly of Earth-like planets I. Terrestrial accretion and dynamics

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What to Expect

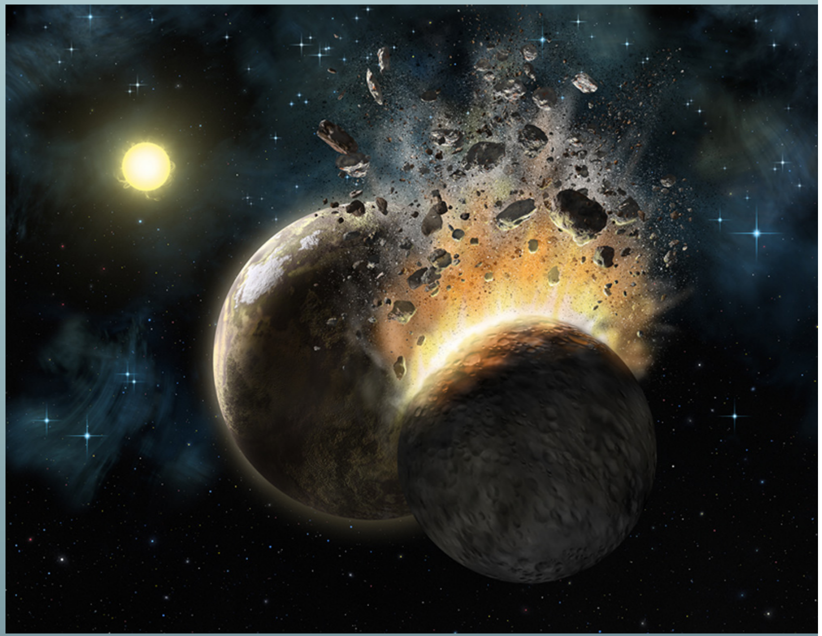
- Background- formation of terrestrial planets
- Need for High Resolution
- Numerical Method
- Initial conditions
- Simulation 0
- Simulations 1a and 1b
- Simulations 2a and 2b
- Conclusions

Final Stages of Formation for Terrestrial planets

- Formation of planetary embryos from planetesimals
- Accretion of embryos into terrestrial planets
- Embryos from in Two steps : Runaway and oligarchic growth

More about Embryos

- 30-50 or 500-1000 embryos formed, depending on mass
- Embryos form faster closer to the Sun
- Formation time unknown: $10^4 - 10^7$ years
- Oligarchic growth ends when 50%-50% mass in embryos and planetesimals
- Final assembly - accretional growth – 50Myr



Lynette Cook/Gemini Observatory

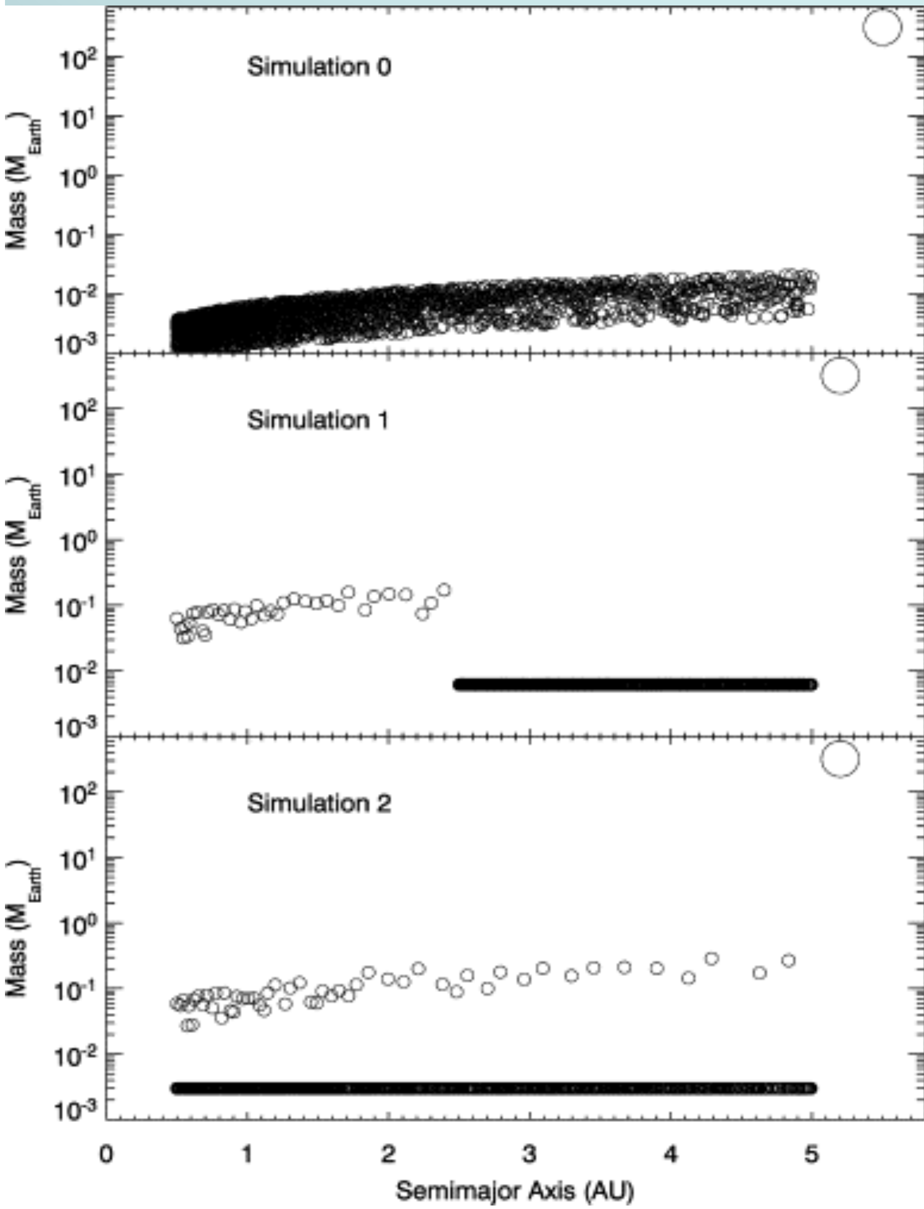
Why High-Resolution Simulations?

- Past simulations limited to 20-200 particles, no sub-lunar size embryos, neglected planetesimals
- Dynamical friction requires large number of particles
- Large number low-resolution
- need better resolution to understand phenomena
- Simulate realistic number of embryos
- Problem- only one simulation and stochastic nature of accretion process

Numerical Method

- Mercury- serial code (Chambers, 1999)
- 5-10X more particles compared to pervious simulations
- Time for simulation scales with number of particles N^2
- 2-16 months of CPU time per simulation run

INITIAL CONDITIONS



Initial conditions for 5 high resolution simulations

Simulation	N (massive)[a]	N (non-int)[b]	M_{TOT} ($M_\oplus$)[c]	a_{Jup} (AU)[d]
0	1885	–	9.9	5.5
1a	1038	–	9.3	5.2
1b	38	1000	9.3	5.2
2a	1054	–	8.6	5.2
2b	54	1000	8.6	5.2

[a] Number of massive, self-interacting particles.
[b] Number of non-self-interacting particles.
[c] Total solid mass in planetary embryos and planetesimals.
[d] Orbital radius of Jupiter-mass giant planet.

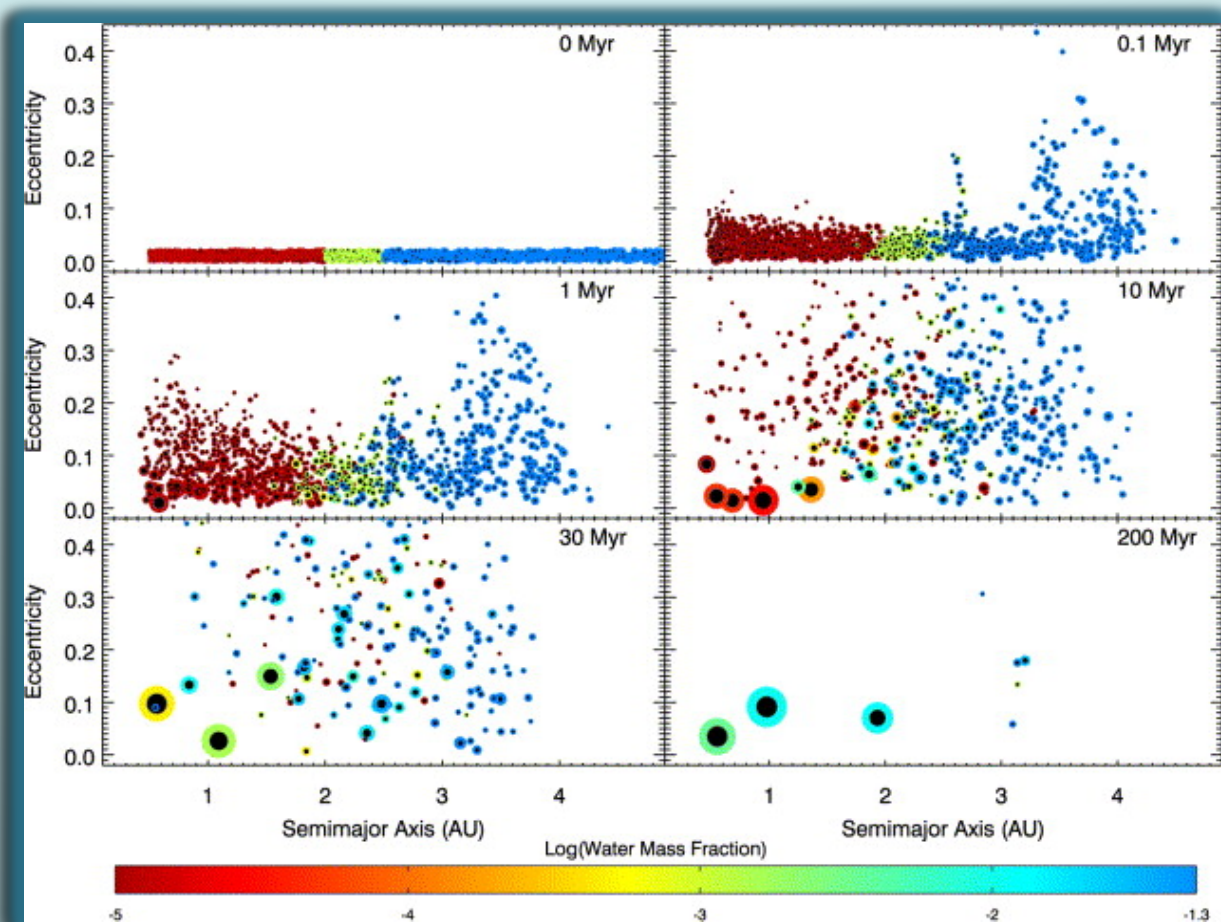
Initial Conditions

- Represent different timescales for the formation of Jupiter and/or formation of embryos
- Did embryos from in the asteroid belt before Jupiter?
- Fast scenario- formed in inner disk before Jupiter
- Slow scenario-embryos start to accrete after Jupiter is formed
- 0-fast formation of Jupiter
- 1- late formation of Jupiter or slow accretion of embryos
- 2 - very late formation of Jupiter or fast embryo formation

Simulation 0

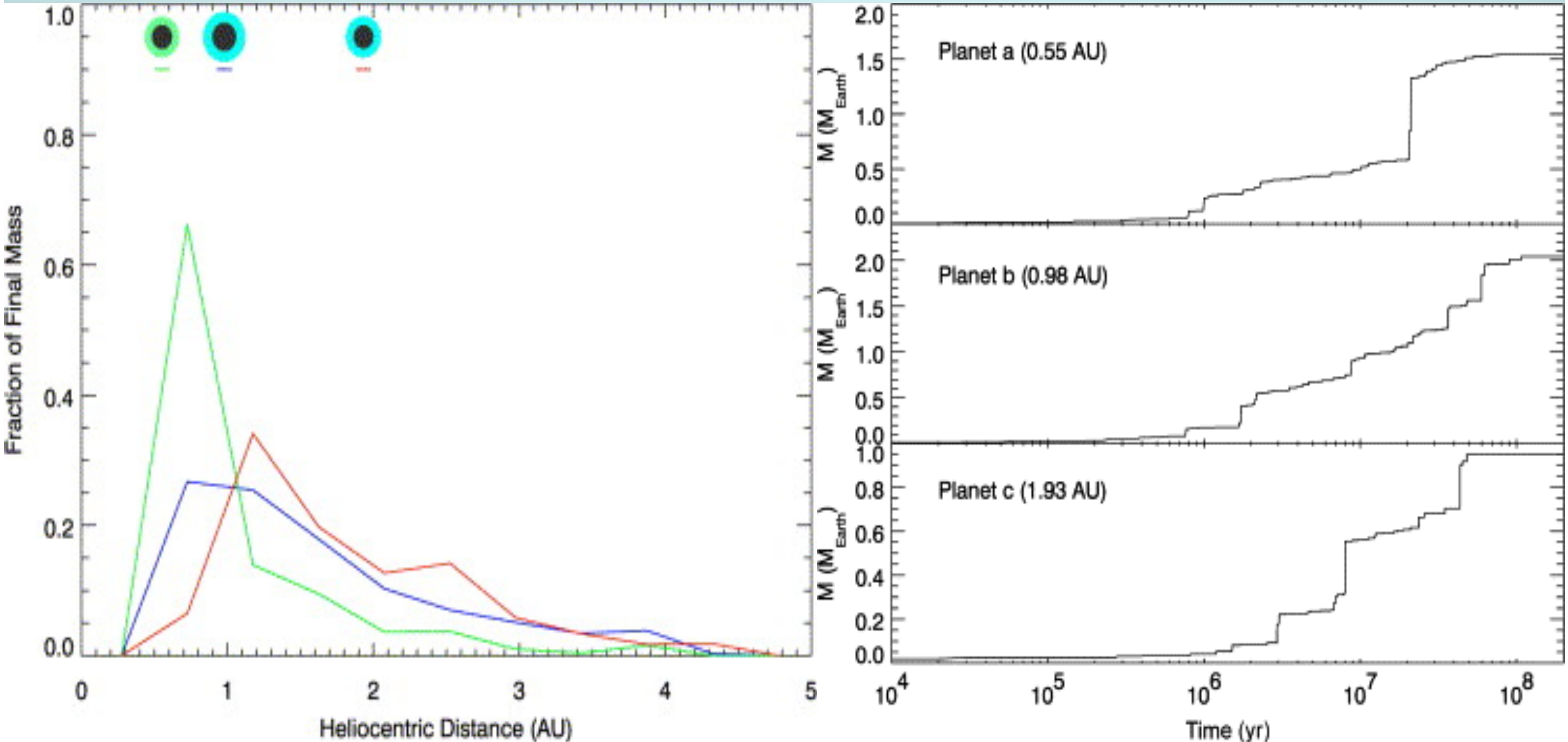
- Starts- Late stage of oligarchic growth
- No planetary embryos formed
- Embryo separation – 0.3 and 0.6 mutual Hill radii
- 1885 Planetesimals
- Simulation runs for 200 Myrs

1885 Particles and self-interacting

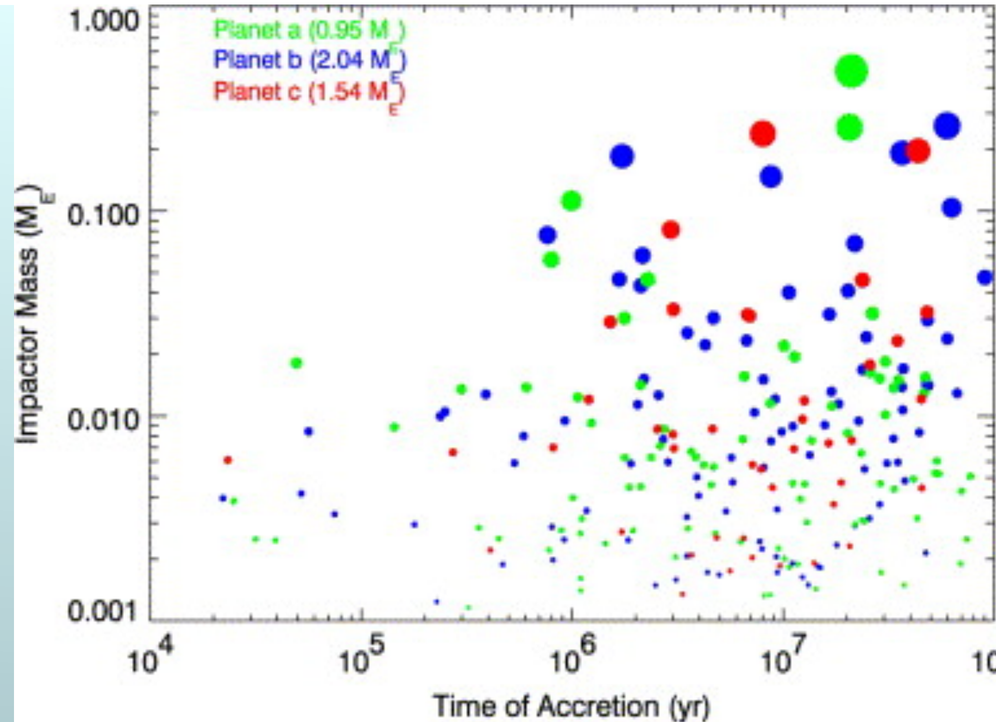


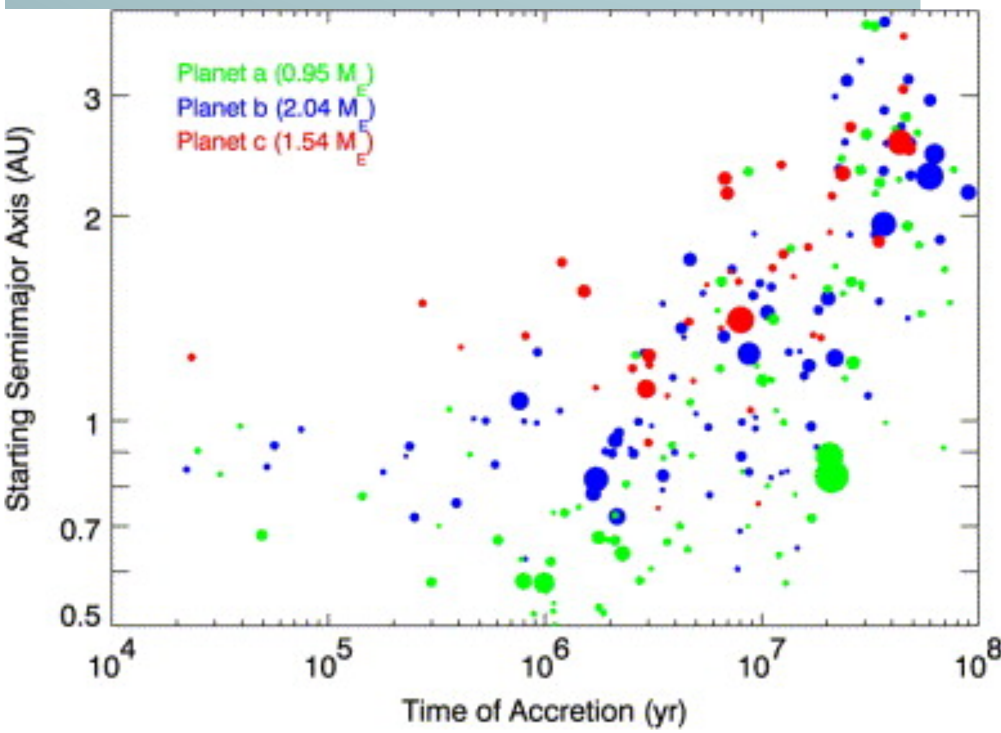
The size of each body corresponds to its relative physical size (i.e., its mass $M^{1/3}$), but is not to scale on the x axis. The color of each particle represents its water content, and the dark inner circle represents the relative size of its iron core.

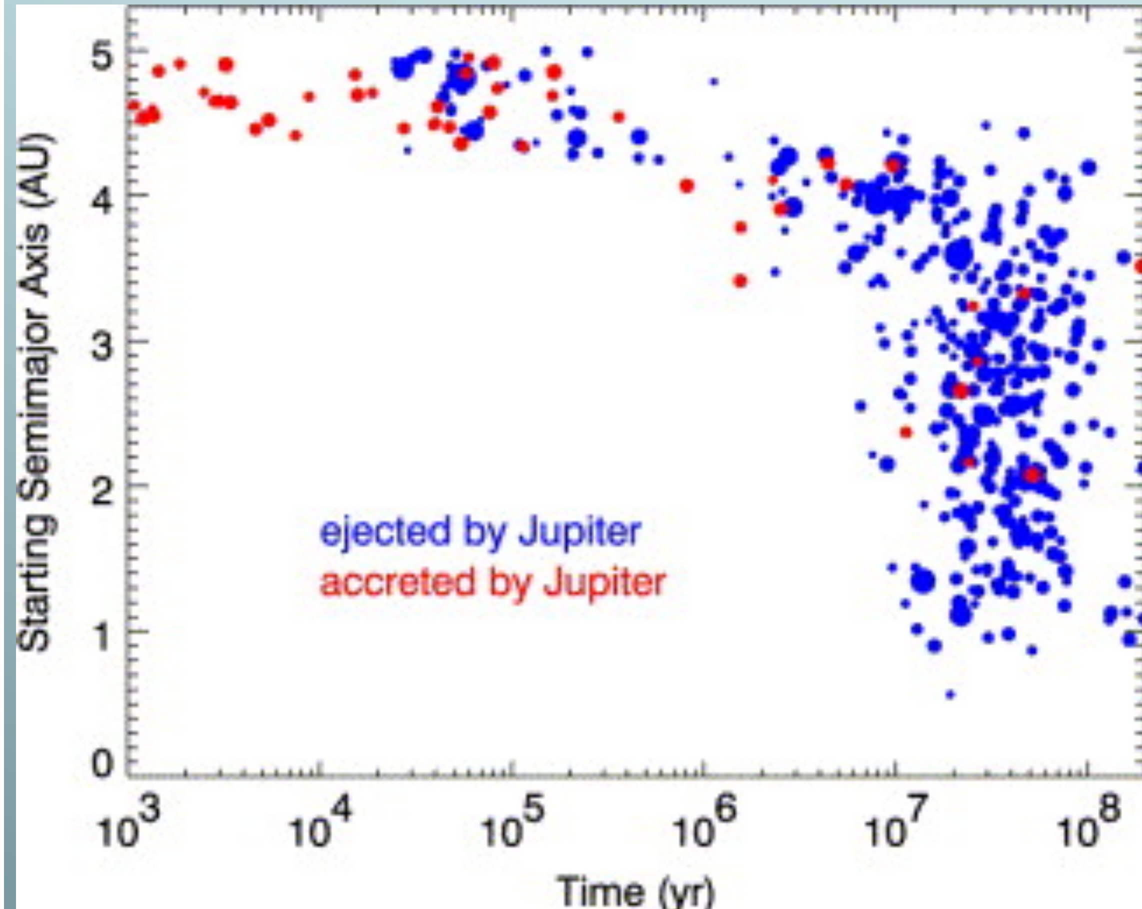
The Feeding Zones!



Accretion of more distant bodies marks the end of oligarchic grown in a region

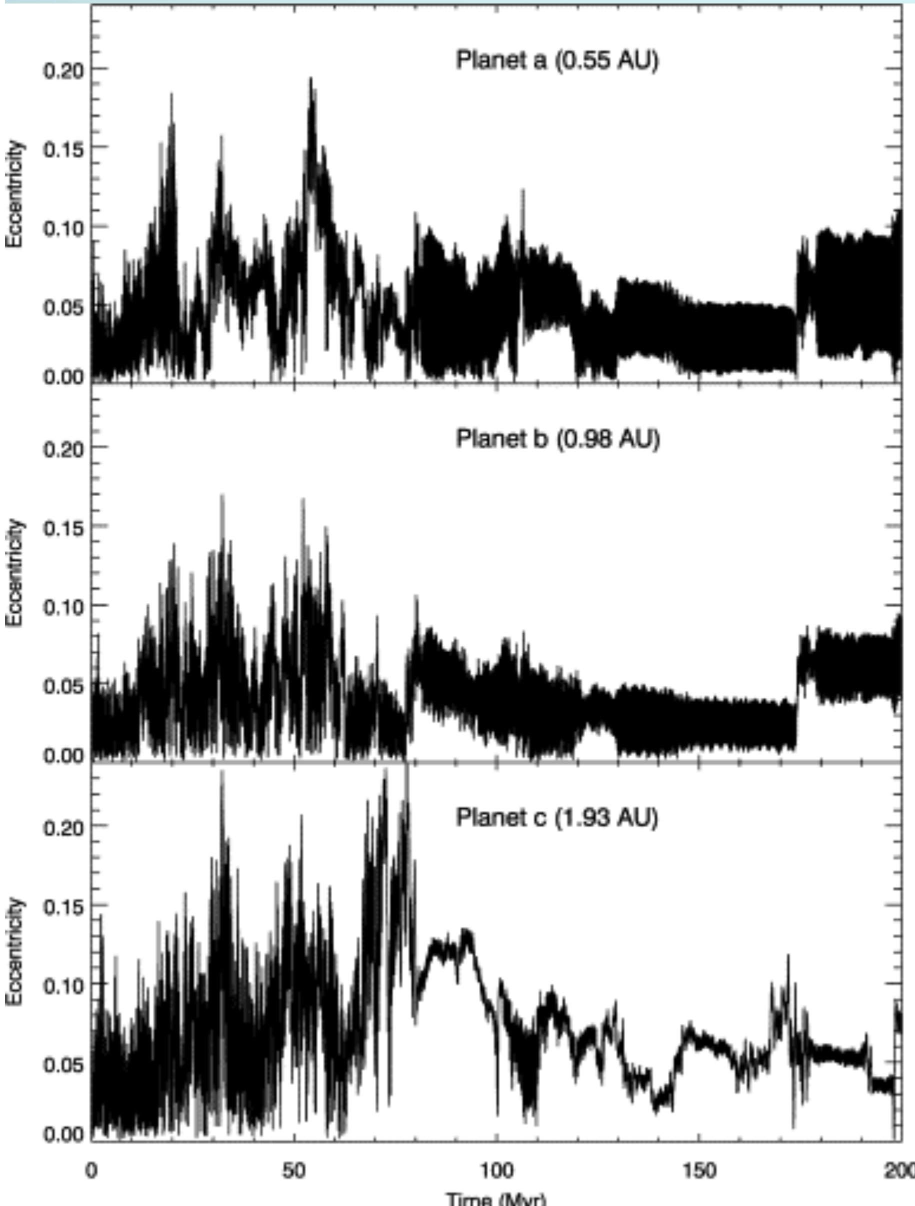




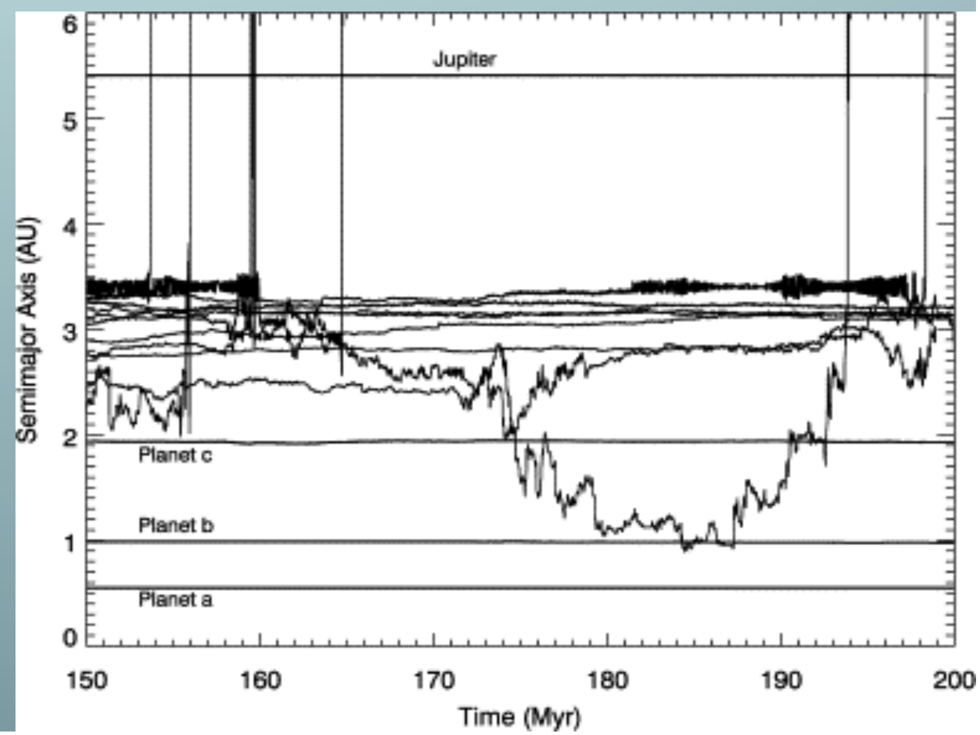


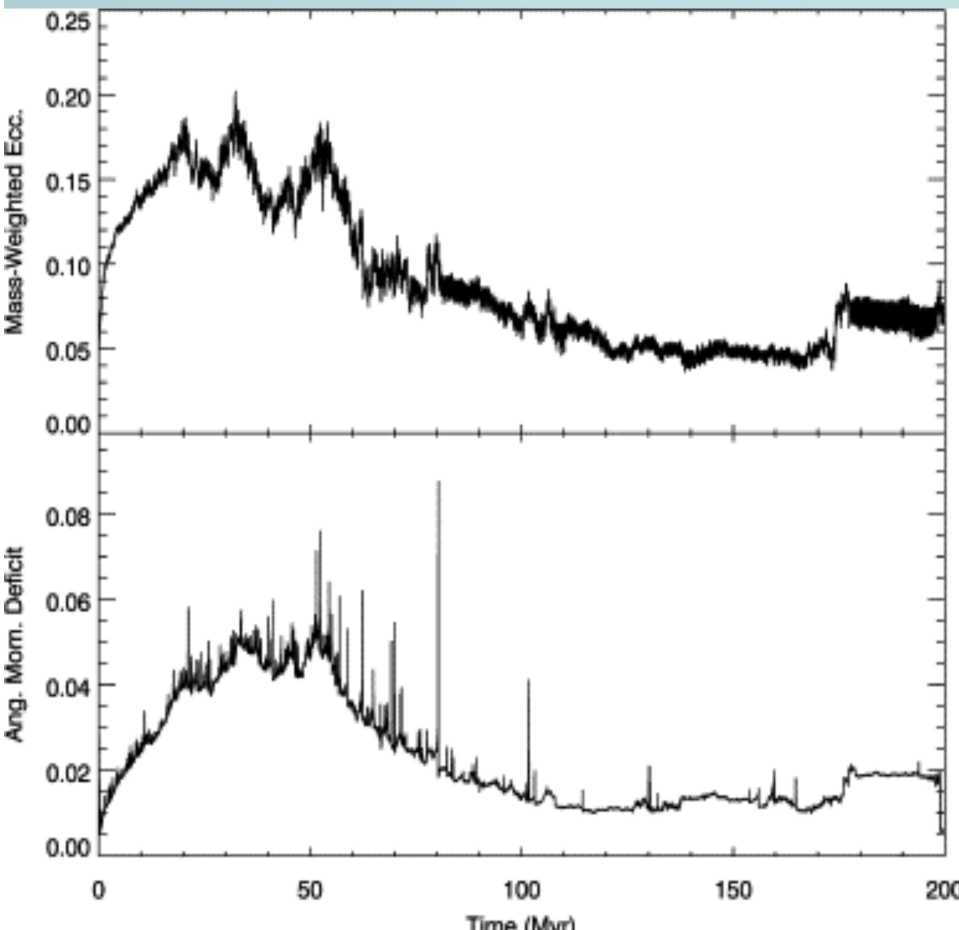
The timing of the ejection and accretion by Jupiter of bodies from different starting locations. Note the change in the "ejection zone" at *t≈10 Myr.*

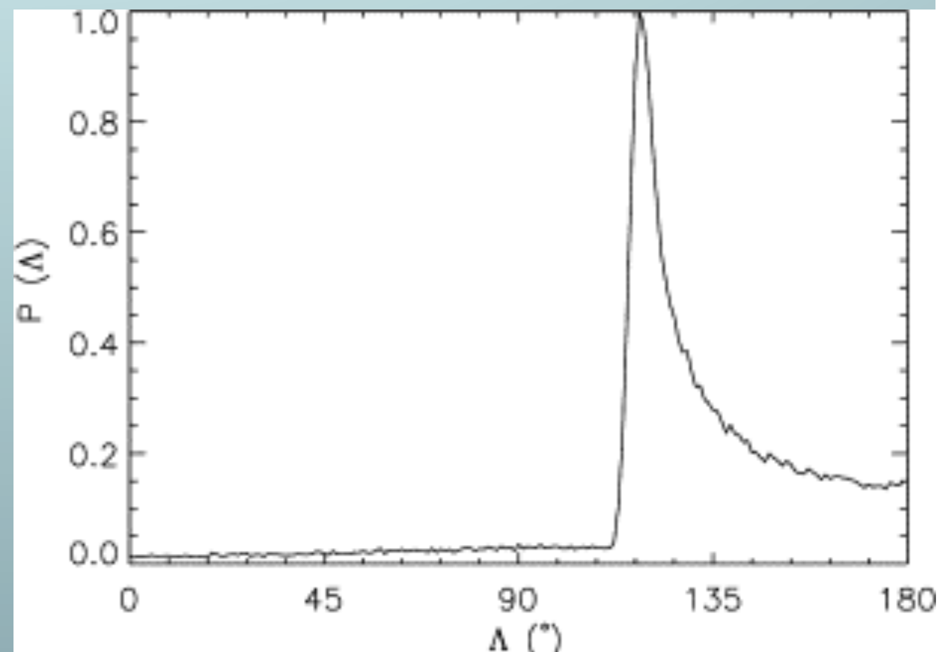
Eccentricity vs time



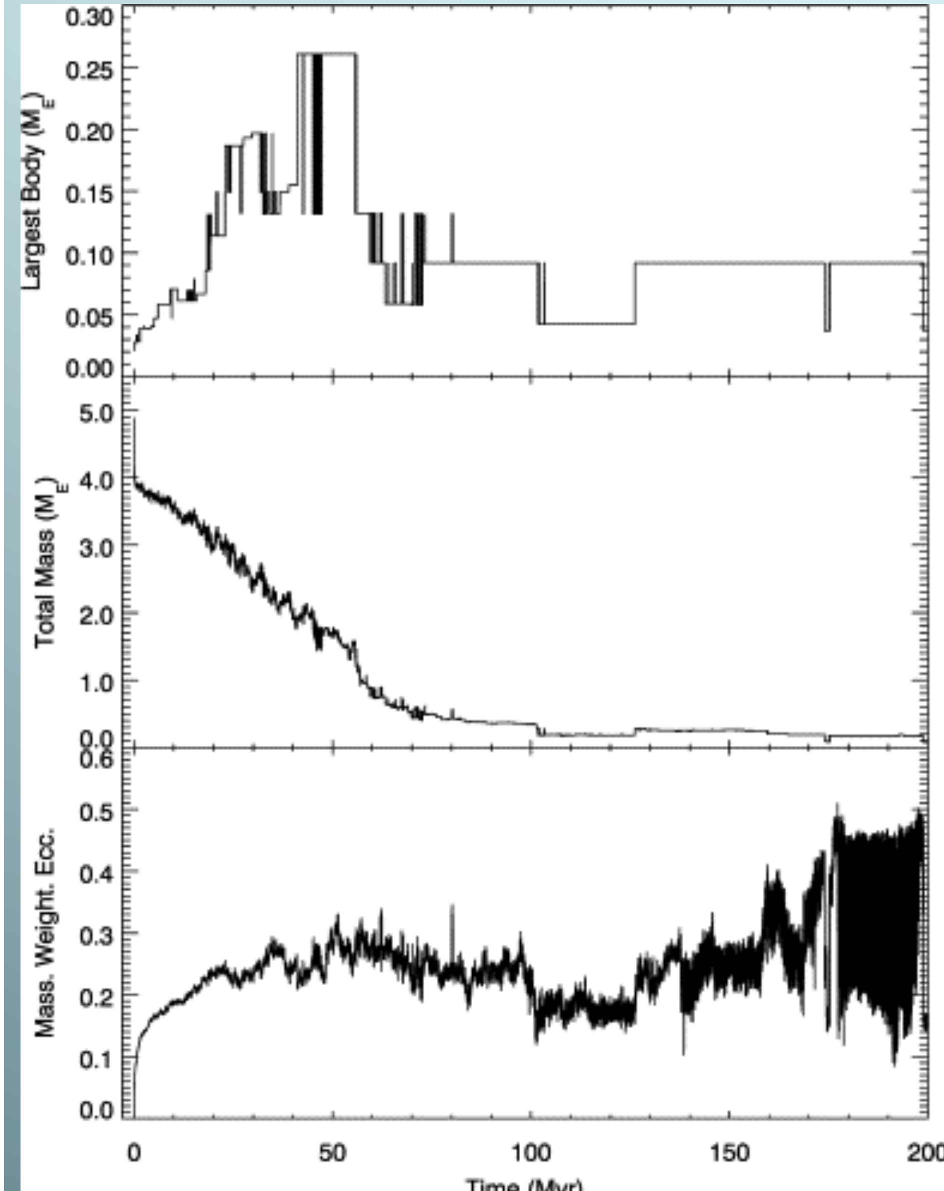
The mean eccentricities for planets *a, b, and c from 100–200 Myr are 0.048, 0.039, and 0.057*




Mass-Weighted Ecc.
Ang. Mom. Deficit
Time (Myr)
0.25
0.20
0.15
0.10
0.05
0.00
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200


P (Λ)
Λ (°)
1.0
0.8
0.6
0.4
0.2
0.0
0
45
90
135
180

Evolution of Asteroid Belt



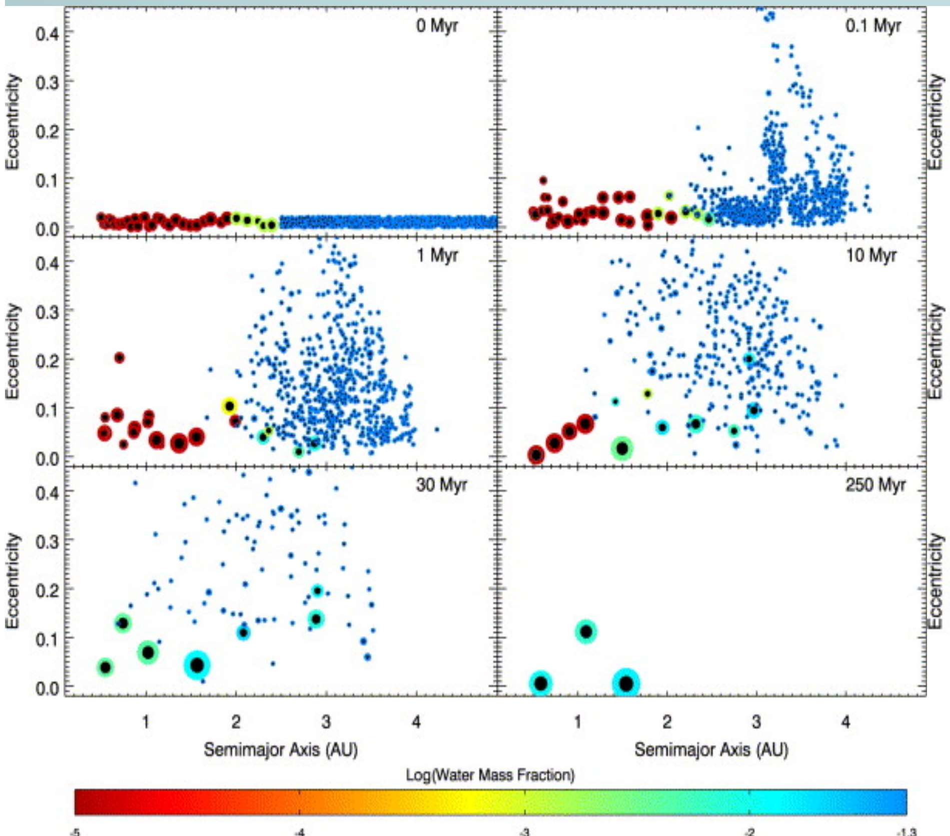
- Evolution of the asteroid belt (defined as 2.2<*a*<5.2 AU) in time for simulation 0. Top: The most massive body in the asteroid belt through time. Middle: Total mass in the asteroid belt as a function of time. Bottom: Mass-weighted eccentricity of all bodies in the asteroid belt over time.

Simulations 1a and 1b

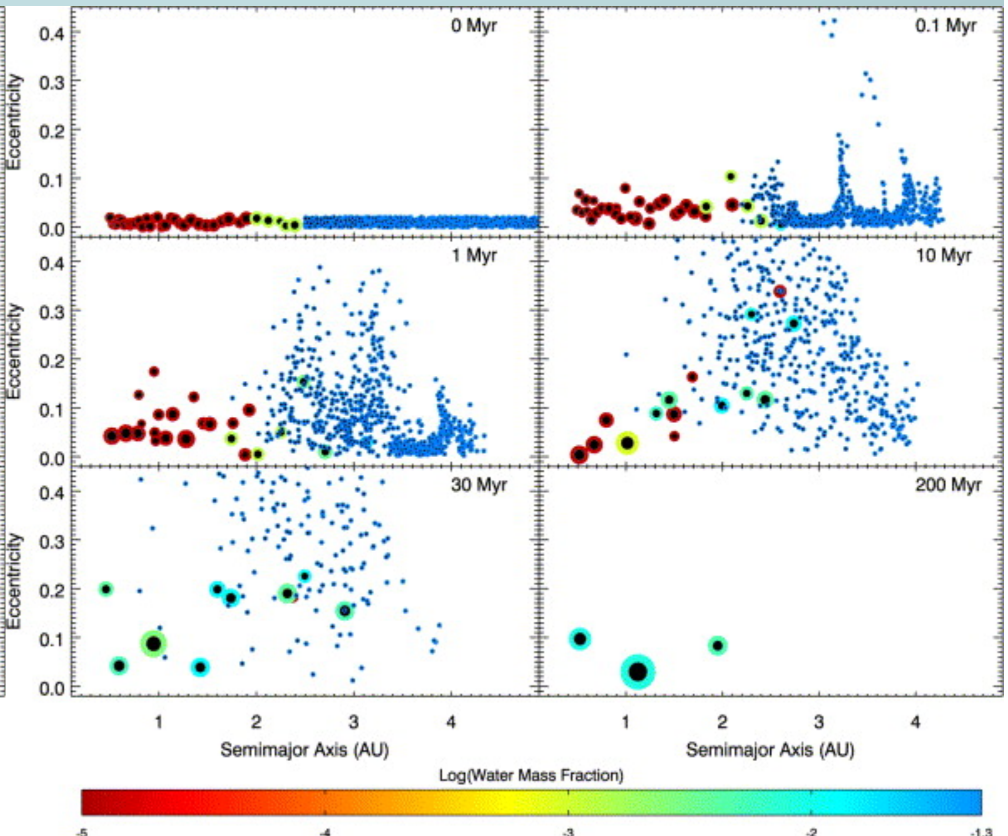
- 38 – planetary embryos out to 2.5 AU
- 1000 – 0.006 M_{Earth} “planetesimals” between 2.5 and 5 AU
- Same starting positions
- 1a-planetesimals are massive bodies which interact gravitationally with all other bodies in the simulation
- 1b-planetesimals feel the gravitational presence of the embryos and Jupiter, but not each other's presence. These non-interacting planetesimals may not collide with each other.

1a and 1b

Self Interacting

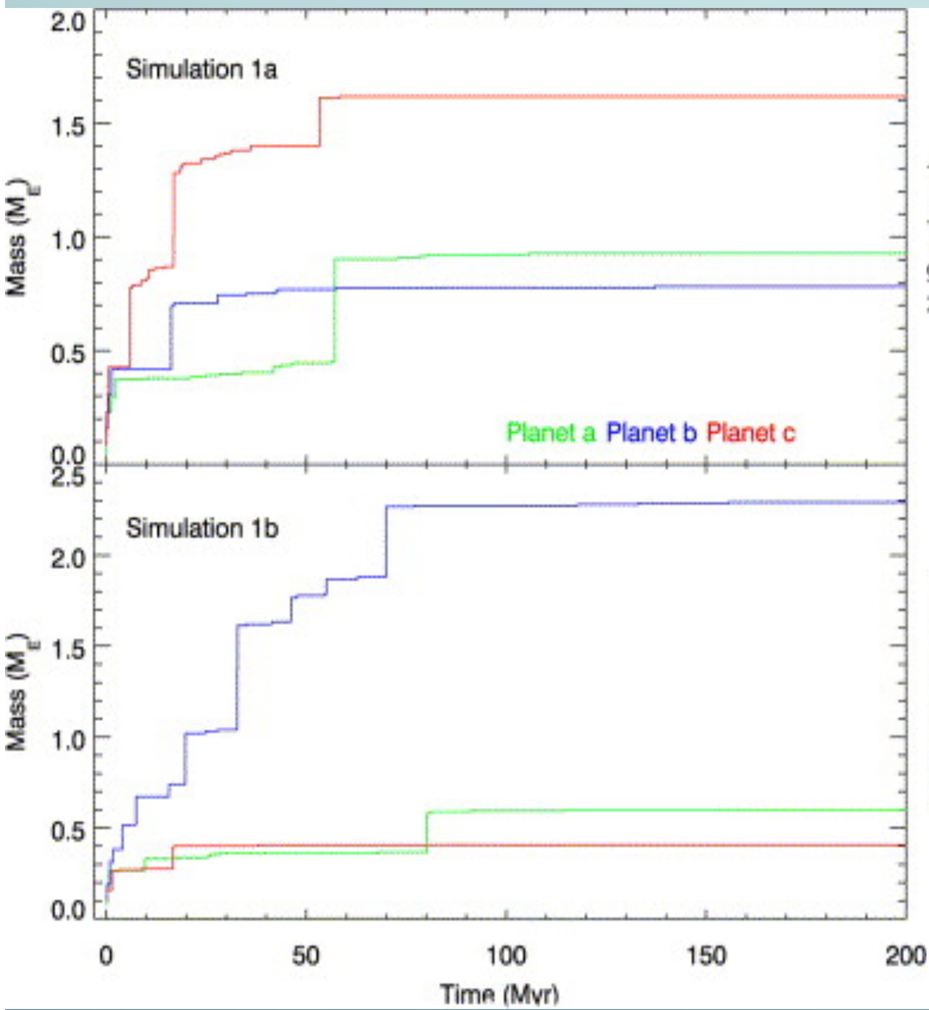


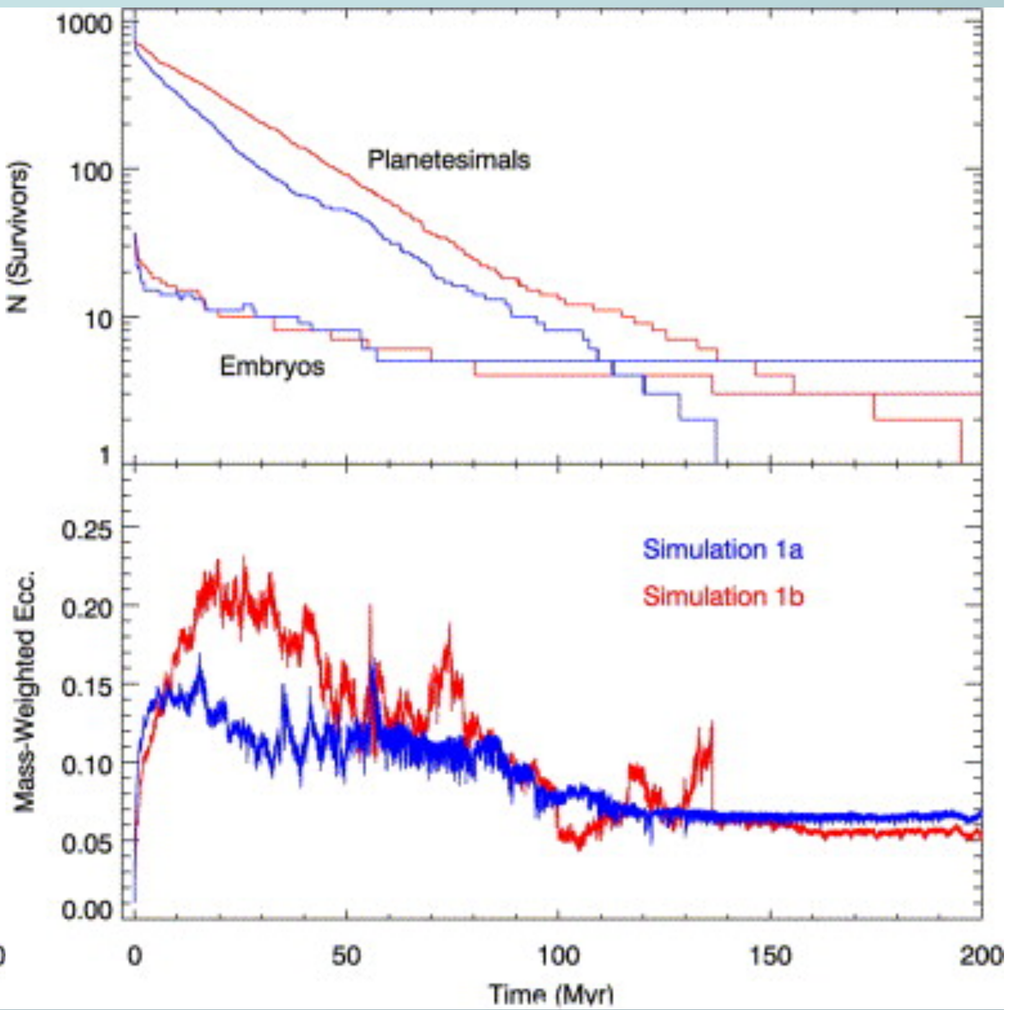
Non self-interacting



Growth of surviving terrestrial planets

Top: Number of surviving bodies
Bottom: mass-weighted eccentricity of surviving bodies





1a and 1b Summary

- Accretion can happen in asteroid belt
- No large embryos formed in asteroid belt
- Run into resolution limit because no planetesimals remain at end of simulations
- Self-gravity accelerates planet fromation

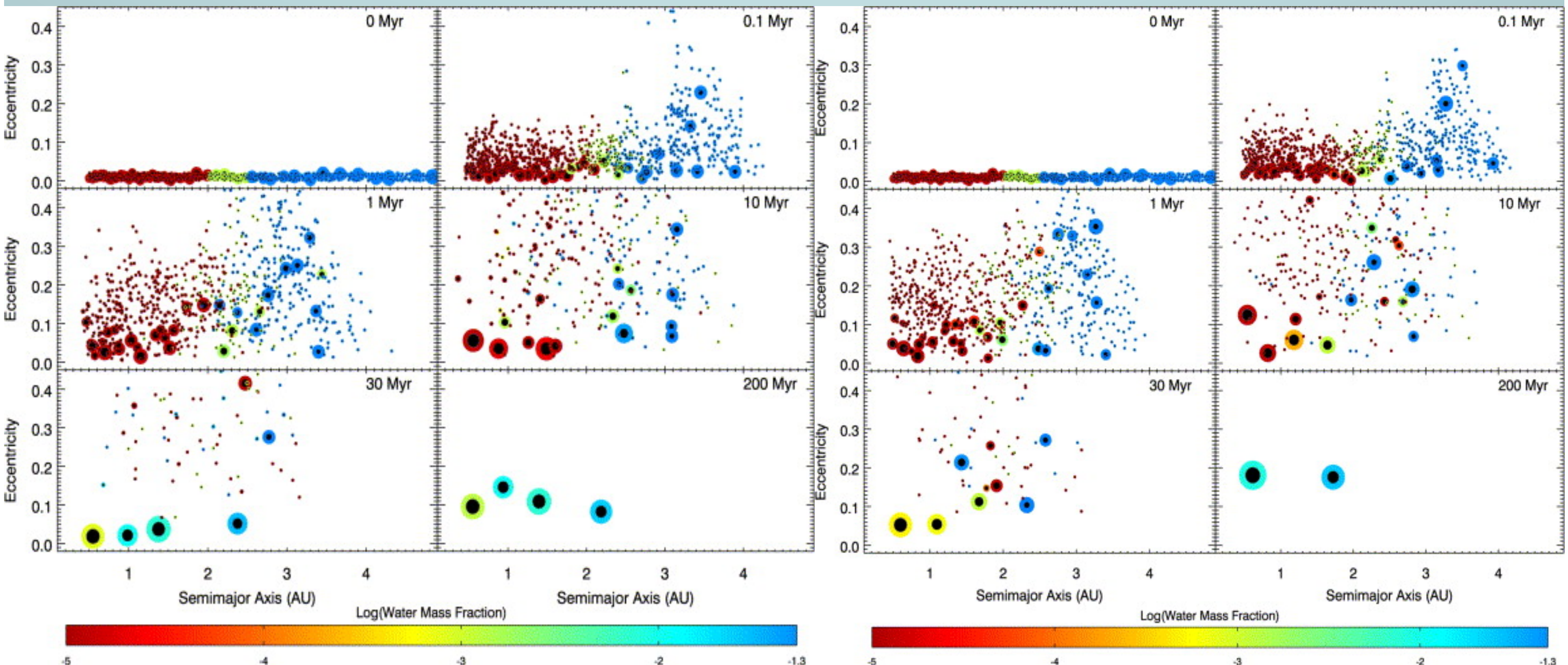
2a and 2b Simulations

- 2a and 2b have identical starting conditions
- 54 planetary embryos throughout the terrestrial region, embedded in a disk of 1000 “planetesimals” of 0.003 M_{earth}
- Mass: 2/3 – embryos, 1/3 – planetesimals.
- Embryos formed all the way out to 5 AU
- 2a all particles are fully self-interacting
- 2b the planetesimals do not feel each other's presence

2a and 2b

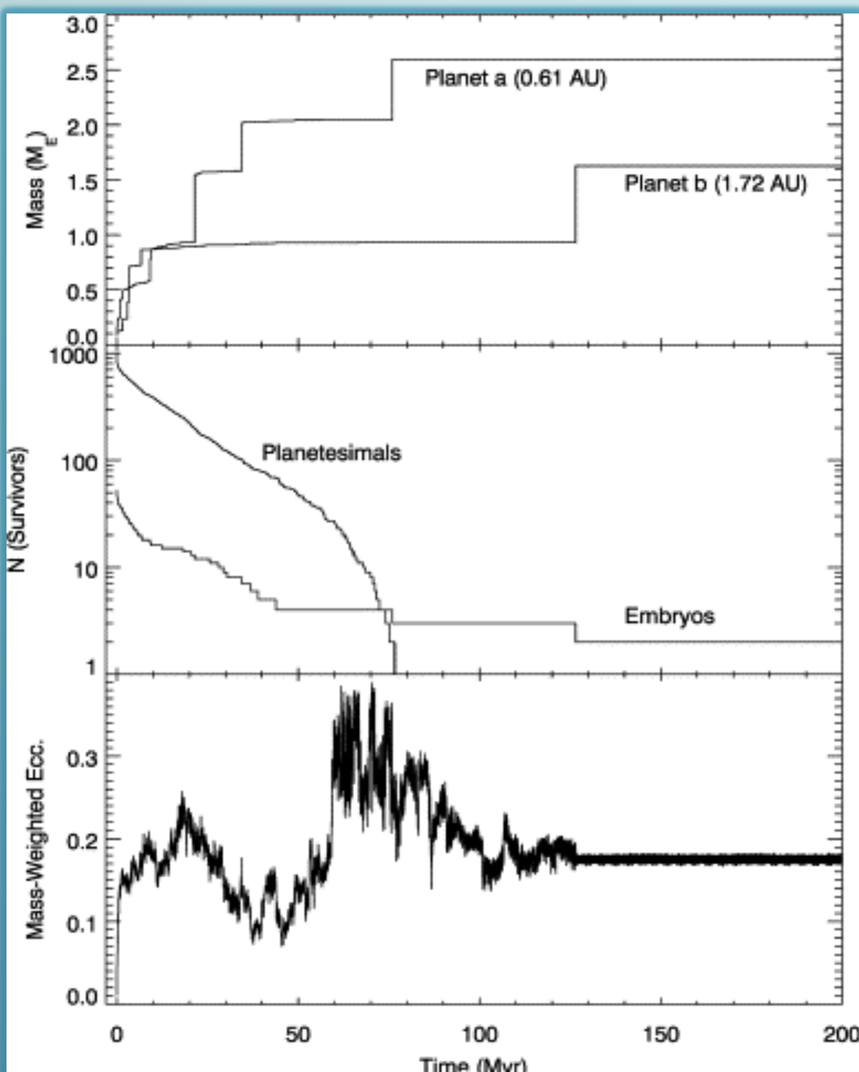
Self-interacting

Non-self-interacting

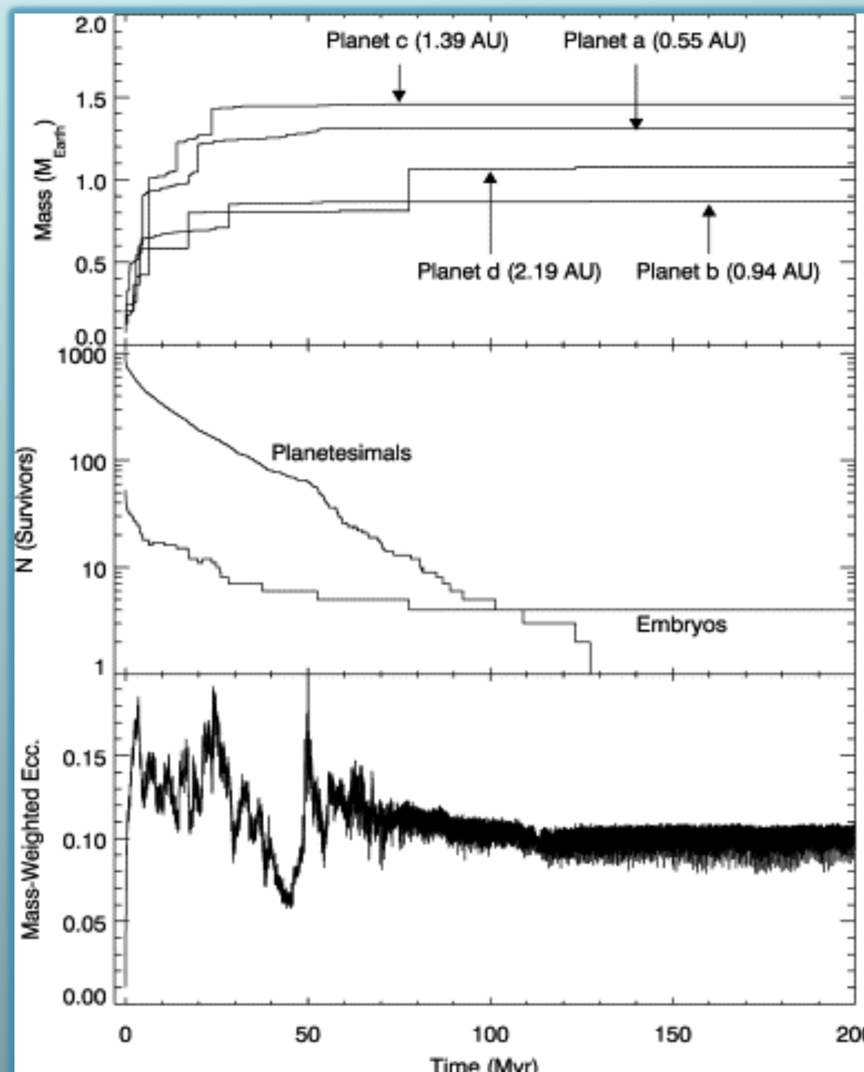


Top: Mass vs Time for surviving planets
Middle: Number of surviving planetary embryos
Bottom: Mass-weighted eccentricity of surviving bodies

2b



2a



Conclusions

– feeding zones of the terrestrial planets widen and move outward in time

– The asteroid belt is cleared of >99% of its mass as a natural result of terrestrial accretion.

– Jupiter possibly stunting growth of embryos beyond 2-3AU

– Dynamical friction is important for the growth of terrestrial planets

– smaller eccentricities

Properties of (**potentially habitable**) planets formed[a]

Simulation	Planet	a (AU)	$\bar{e}$[b]	$\bar{i}$ (°)[c]	M ($M_\oplus$)	W.M.F.	N (oceans)[d]	Fe M.F.
0	a	0.55	0.05	2.8	1.54	2.6×10^{-3}	15	0.32
	b	**0.98**	**0.04**	**2.4**	**2.04**	$\mathbf{8.4 \times 10^{-3}}$	**66**	**0.28**
	c	1.93	0.06	4.6	0.95	9.1×10^{-3}	33	0.28
1a	a	0.58	0.05	2.7	0.93	8.3×10^{-3}	30	0.31
	b	**1.09**	**0.07**	**4.1**	**0.78**	$\mathbf{5.5 \times 10^{-3}}$	**17**	**0.30**
	c	1.54	0.04	2.6	1.62	1.2×10^{-2}	75	0.26
1b	a	0.52	0.06	8.9	0.60	7.2×10^{-3}	17	0.31
	b	**1.12**	**0.05**	**3.5**	**2.29**	$\mathbf{6.7 \times 10^{-3}}$	**60**	**0.29**
	c	1.95	0.09	9.7	0.41	3.8×10^{-3}	6	0.28
2a	a	0.55	0.08	2.6	1.31	9.3×10^{-4}	5	0.33
	b	**0.94**	**0.13**	**3.4**	**0.87**	$\mathbf{8.6 \times 10^{-3}}$	**29**	0.29
	c	**1.39**	**0.11**	**2.4**	**1.46**	$\mathbf{6 \times 10^{-3}}$	**34**	0.29
	d	2.19	0.08	8.8	1.08	1.8×10^{-2}	75	0.24
2b	a	0.61	0.18	13.1	2.60	7.1×10^{-3}	71	0.30
	b	1.72	0.17	0.5	1.63	2.0×10^{-2}	126	0.22
Mercury[e]		0.39	0.19	7.0	0.06	1×10^{-5}	0	0.68
Venus		0.72	0.03	3.4	0.82	5×10^{-4}	1.5	0.33
Earth		**1.0**	**0.03**	**0.0**	**1.0**	$\mathbf{1 \times 10^{-3}}$	**4**	**0.34**
Mars		1.52	0.08	1.9	0.11	2×10^{-4}	0.1	0.29