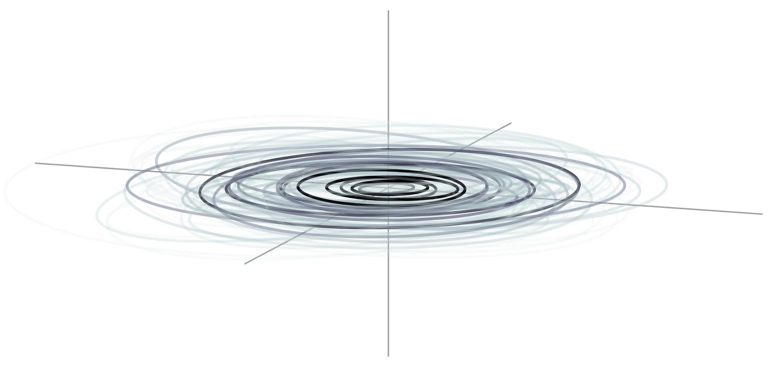
Stochasticity in Terrestrial Planet Formation



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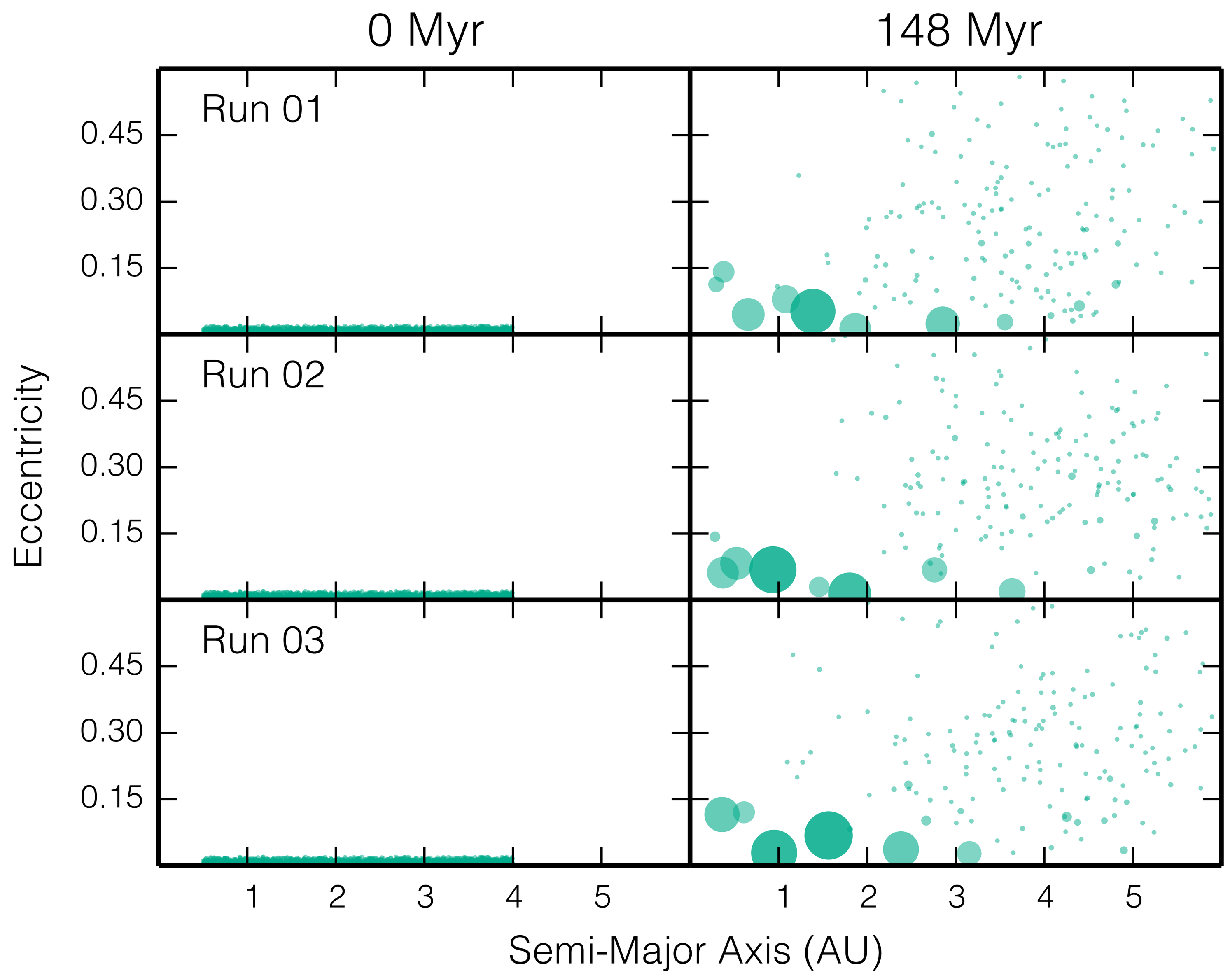
Same Disk, Different Planets

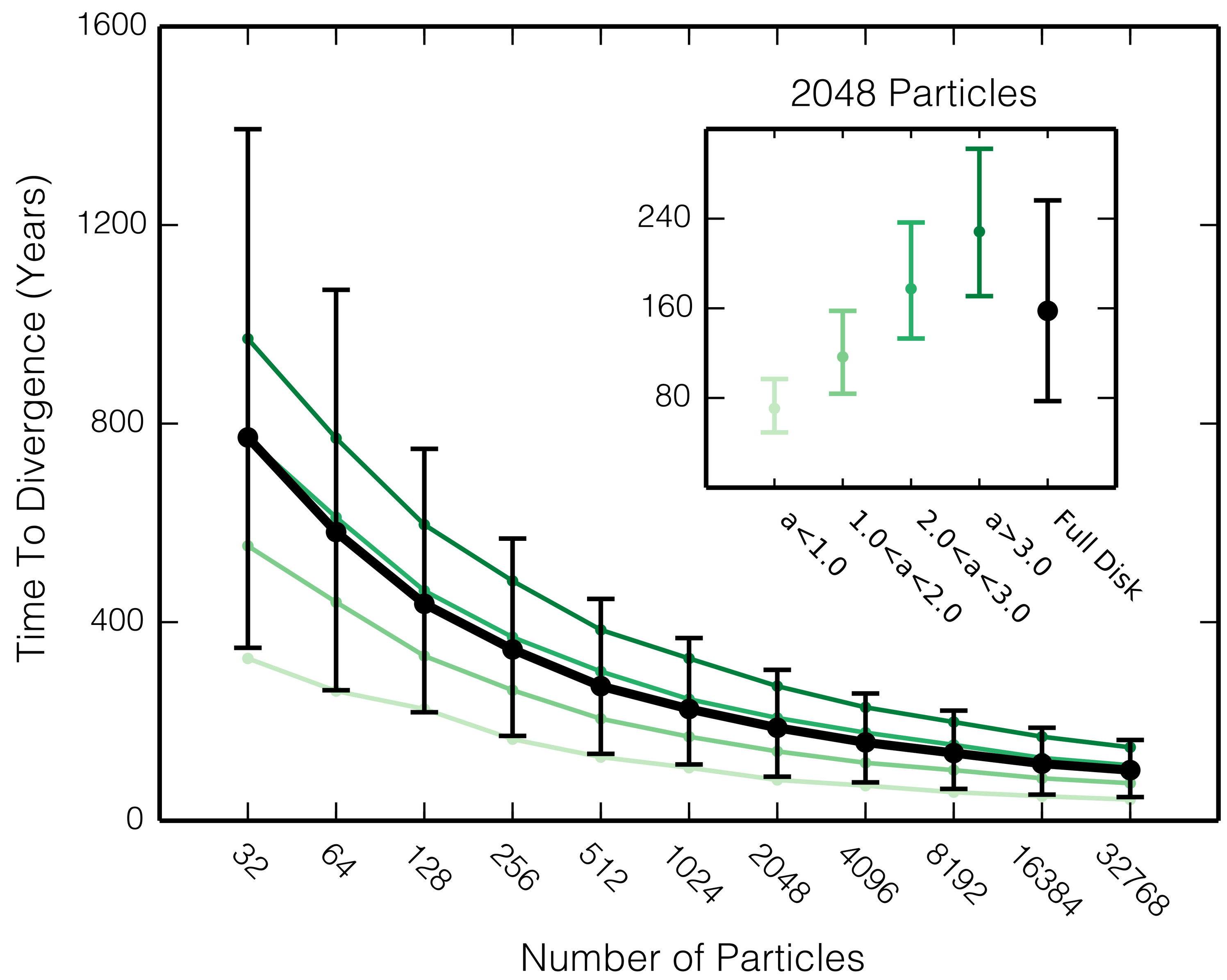
Terrestrial planet formation simulations evolve stochastically, such that identical initial conditions evolve into different planetary systems (Kokubo+ 2006, Raymond+ 2009). Computational constraints have thus far discouraged characterisation of stochasticity, and resources were allocated towards parameter space sweeps instead.

We investigate the range of final systems by evolving three sets of initial conditions 12 times. Initially, we spread 2000 planetesimals with a total mass of 5 Earth Masses between 0.5 and 4 AU. We use the GPU code Genga (Grimm+ 2014) to track the collisional evolution. Jupiter and Saturn are included in some runs.

Three initially identical simulations are shown on the right. No giant planets were included. Larger circles indicate more massive planets. After 148 Myr, all simulations yield different planetary locations and masses.



Orbits Diverge in 400 Years



Simulations operate with finite numerical precision. This induces truncation errors. To accelerate code execution, compilers and task schedulers can reorder operations. If the order of operations of two simulations differs, the truncation errors differ. Eventually, differences grow large enough to affect the collisional history. At this stage, simulations have diverged.

To estimate the time to divergence, we track orbital separations across a reference and a perturbed run, and enforce the order of operations. The perturbed disk is generated from the reference by displacing particles at the level of machine precision to mimic truncation errors. Once the orbital separation corresponds to the Hill radius, orbits have diverged.

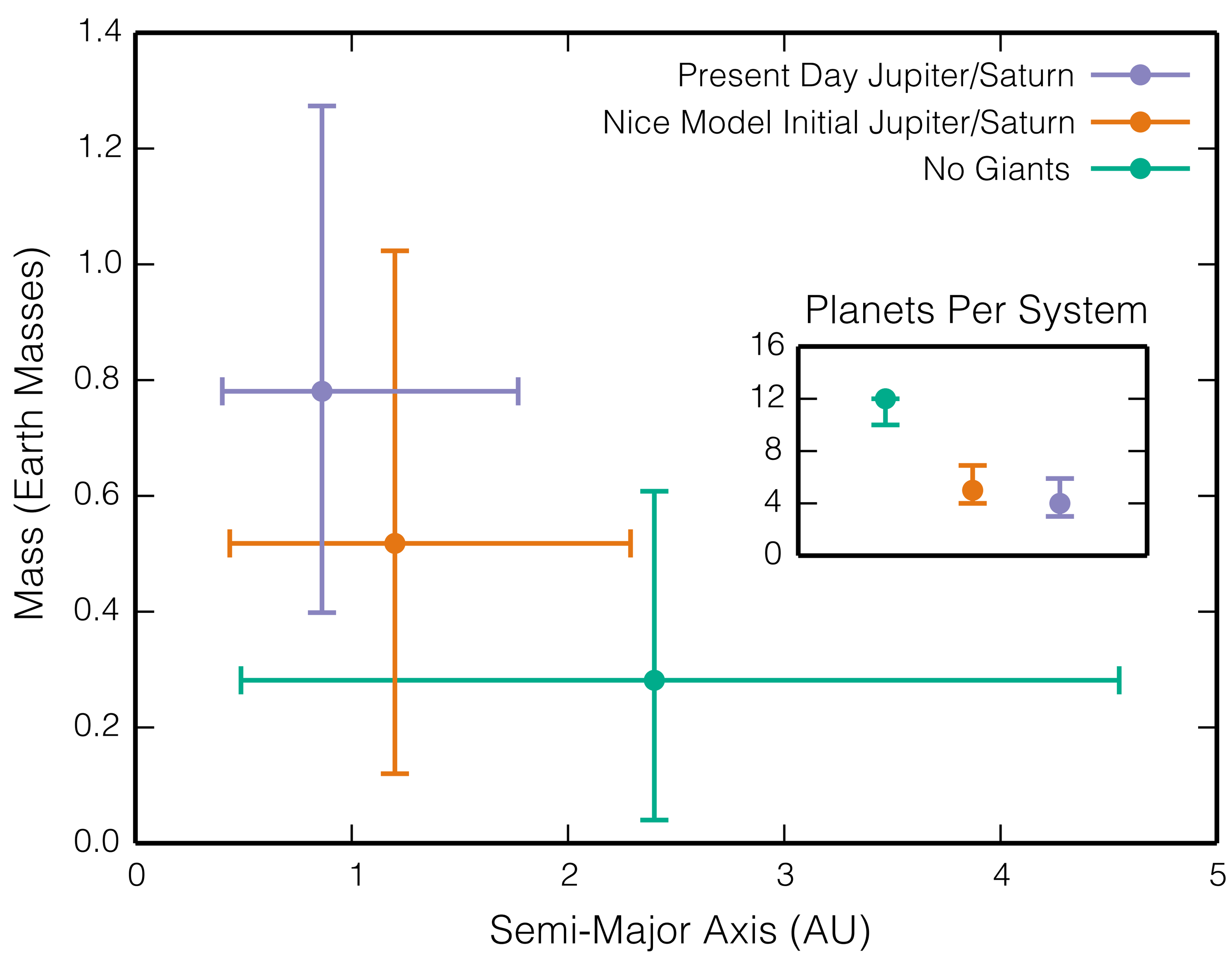
We show the median time for orbits to diverge on the left. Errorbars are 10% and 90% ranges. The more initial particles in the disk, the faster the divergence. Orbits also diverge faster at smaller semi-major axes. In both cases, interactions are stronger due to tighter packing of particles. This accelerate propagation of errors.

Treat Outcome Statistically

The statistical spread in outcomes for the same initial disk can be significant. On the right, we show median planetary mass, semi-major axis, and number of planets per system for three initial conditions. Errorbars are 10% and 90% ranges. Initial conditions are one isolated planetesimal disk, and two disks with Jupiter and Saturn in different configurations.

The isolated disk initial conditions tend to produce planets that are more numerous, lighter, and further from the host star. Including Jupiter and Saturn generates systems with fewer, but heavier planets closer to the host.

Overlapping errorbars emphasize the need for a statistical approach. If we were to run only one simulation for each initial condition, we could end up with pathological case where all three produce similar outcomes. We would then draw wrongful conclusions about the importance of the initial parameters.



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