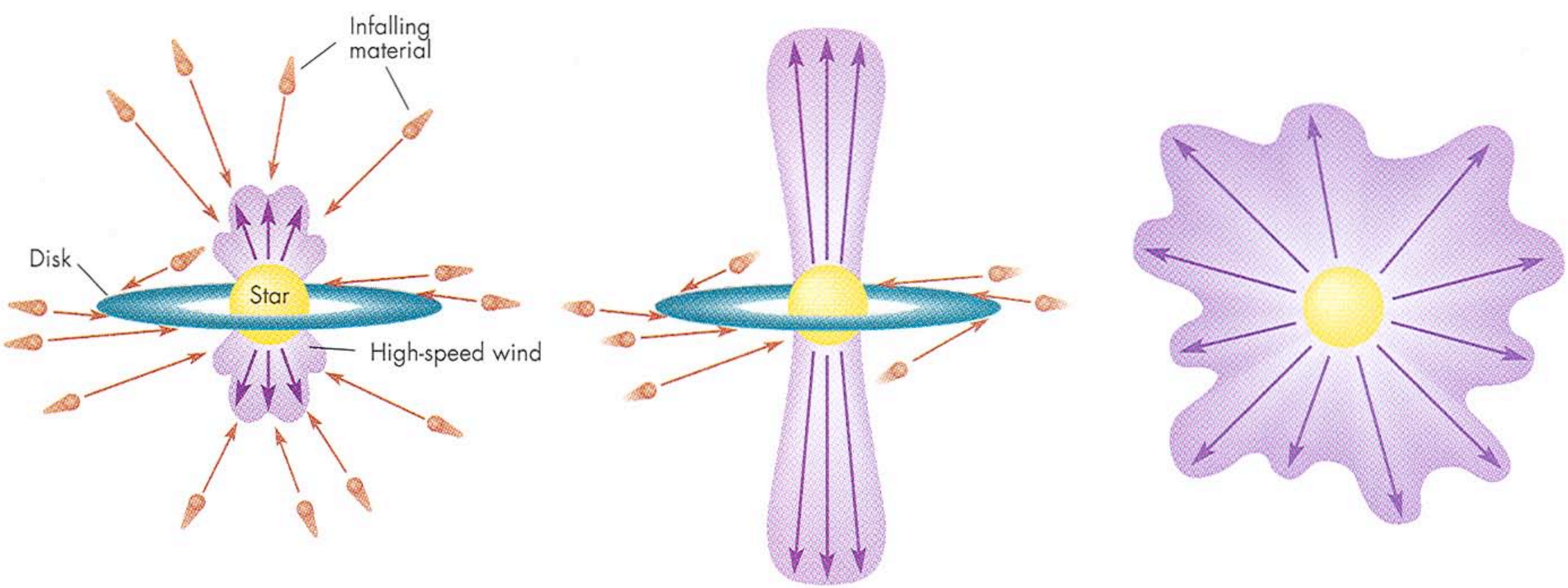
Extrasolar Planets

- Given disks, what are the main theoretical models for how planets formed? (This pdf file)
- What techniques are available for actually *observing* extrasolar planets?
- What have we learned from the ~ 140 planets disovered so far?
- The potential for *direct* detection of planets and biosignatures in their spectra

Basic problem: how frequently do planets manage to form in a rotating disk of gas and dust, in the presence of a powerful wind that will eventually blow most of the gas disk away? And what kinds of planets?

Three Stages in the Development of a Wind

A, The wind is suppressed by infalling material. **B,** Gaining strength, the wind breaks through the infalling material along the polar axis of the star. **C,** Later, the wind may blow outward in all directions and sweep away the disk of orbiting material.



A Infalling material suppresses the wind.

B Eventually the wind becomes strong enough to break through along the polar axes.

C Later the wind sweeps away the disk and blows outward in all directions.

The basic scenario for evolution of planetary systems

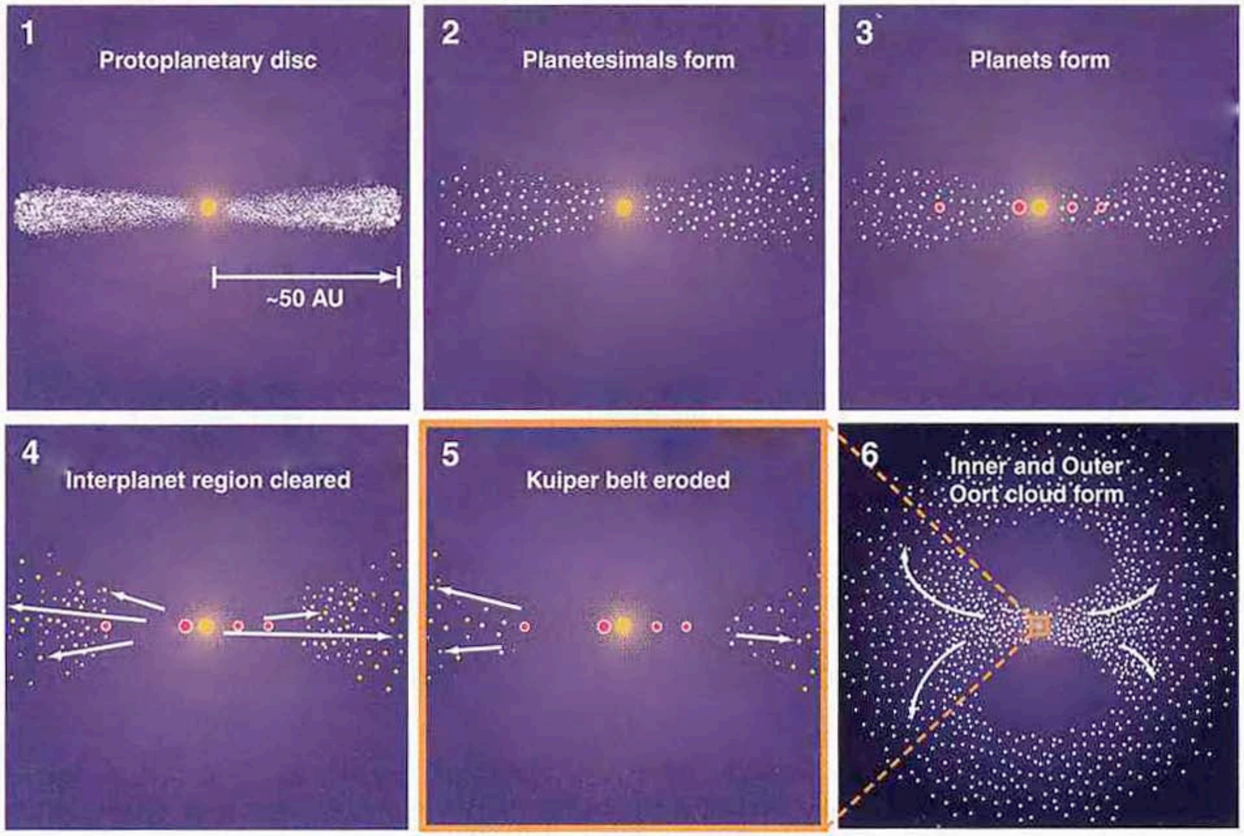
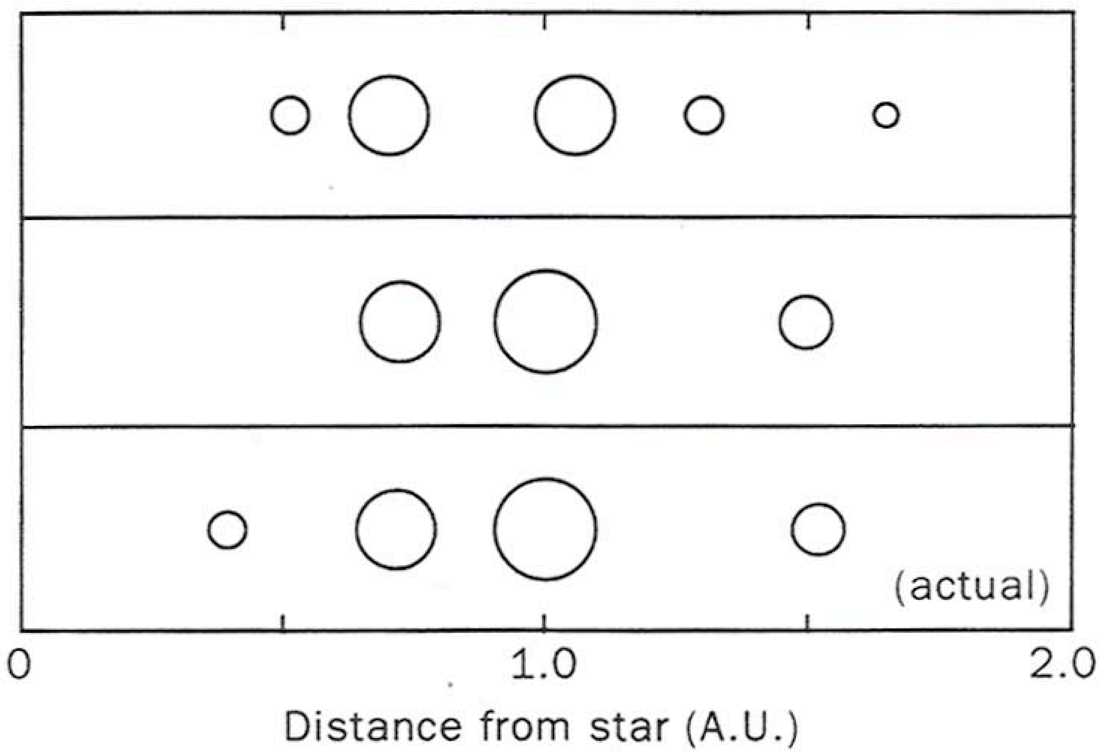


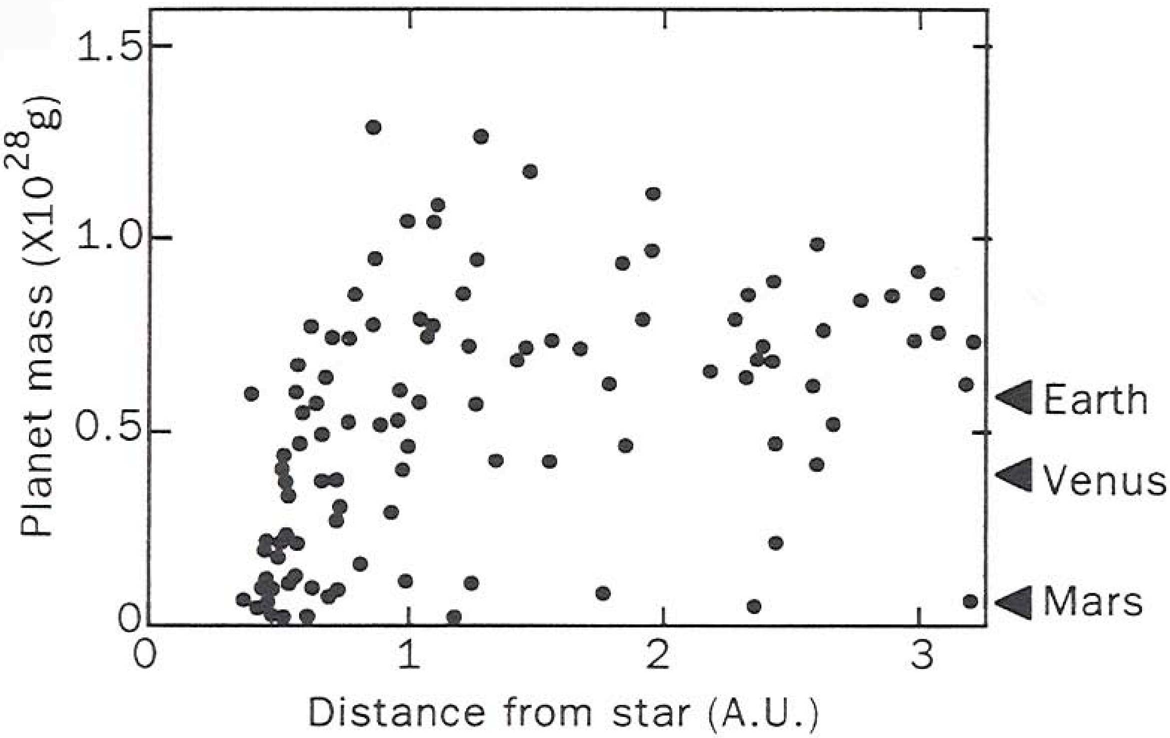
Fig. 2. Strawman model of the evolution of the solar system's comet reservoirs. (1) A flattened accretion disk of gas and dust generates (2) planetesimals through solid-body accretion. The Kuiper belt region is built during this period. The outer planets form (3) in this planetesimal disk and rapidly (in 1 to 10 million years) deplete the interplanet region (4) by hurling the planetesimals out to the scattered disk. On a similar or slightly longer time scale, the Kuiper belt exterior to Neptune is eroded (5) and has its orbital distribution excited. Most of the dispersed objects are placed in the scattered disk (yellow) with large semimajor axes. Those with aphelia thousands of astronomical units away are perturbed by galactic tides and/or passing stars into the inner Oort cloud, whereas those with distances out beyond 10,000 AU are dispersed into the roughly spherical outer Oort cloud (6).

Results of simulations of colliding, coalescing (sticking), planetesimals in a disk. Assumed initial sizes were already ~ 1 km (big problem getting them that large).. Can see that sizes and separations resemble the inner planets of our solar system.



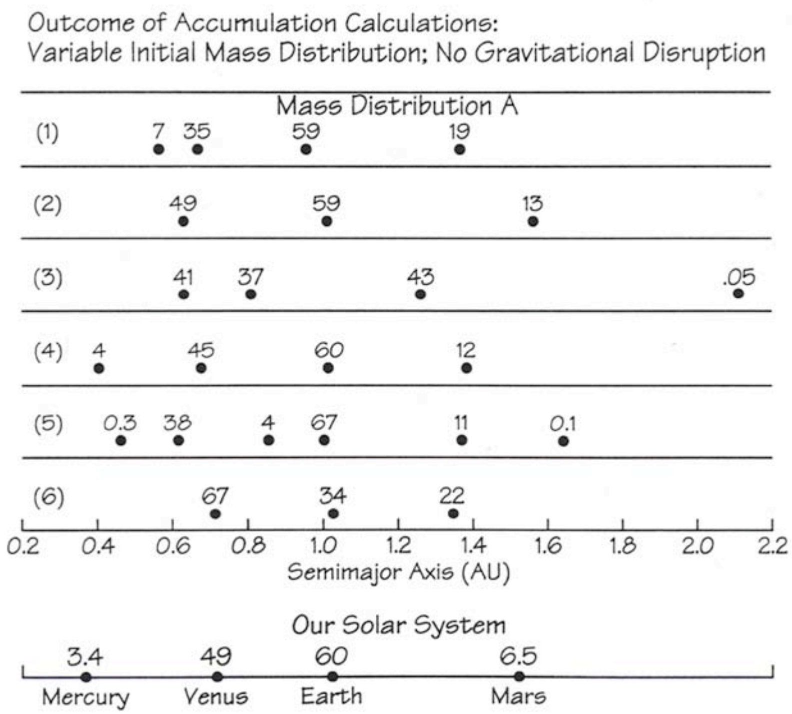
Results of simulations of the formation of planets in a protoplanetary disk. The top two panels show the planets that resulted from a single simulation each, obtained using initial conditions that differ randomly. The bottom panel shows the planets in the inner part of our own solar system. (After Wetherill, 1996.)

Mass vs. distance from star for 33 simulations of collisional coalescence of planetesimals in a disk, all with randomly chosen initial conditions.



Results of simulations of the formation of planets in a protoplanetary disk around a Sun-like star. The results from 33 different simulations (with different initial conditions) are shown together, in order to give a sense of where planets can form and how massive they would be. For each planet formed, the final mass and the distance from the central star are shown; the masses of Earth, Venus, and Mars are indicated for reference. In these simulations, no effects have been included due to the presence of Jupiter. (After Wetherill, 1991.)

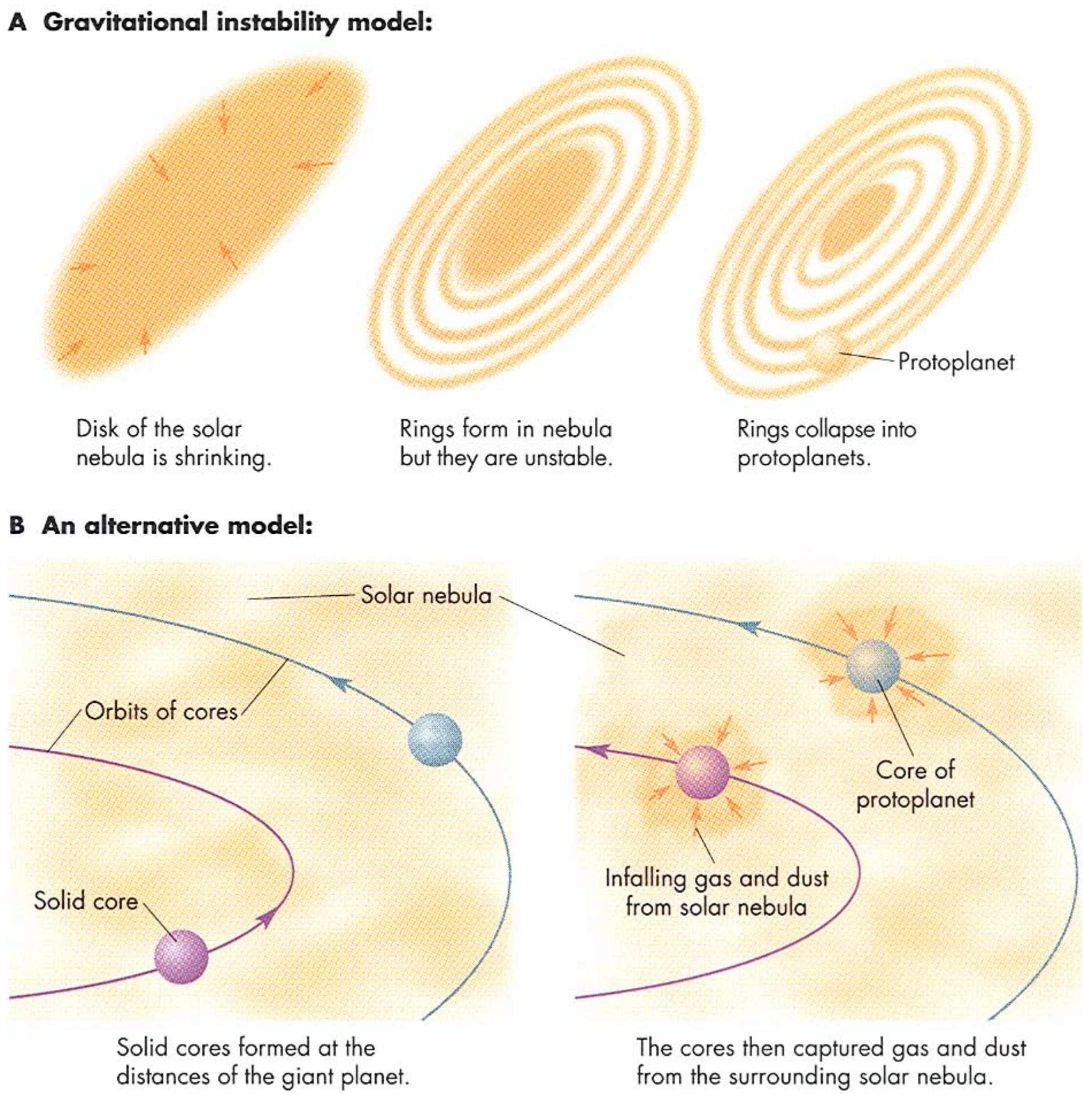
Another view of some of the systems that formed in the collisional simulatons, compared with the inner solar system



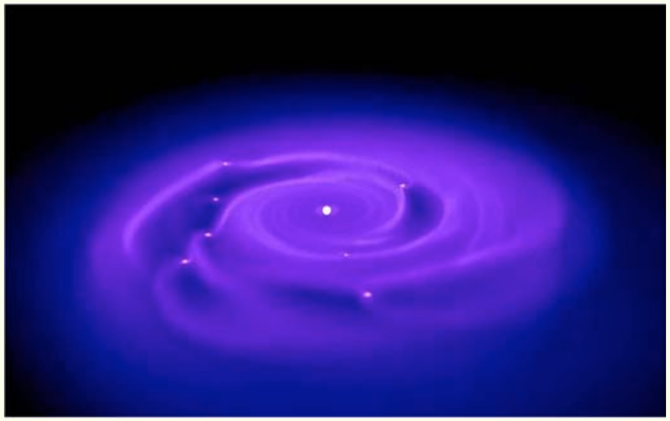
Masses, semimajor axes, and eccentricities for six theoretical simulations of the formation of the terrestrial planets.[5] *Our solar system is shown at the bottom for comparison; the numbers associated with each planet give its mass in units, where 60 is the mass of Earth. The calculations follow the accumulation of the planets through collisions within an initial swarm of lunar-sized bodies. Even though each of these simulations started with the same energy and angular momentum, because of the random nature of planet formation by accumulation, the result is not always four planets. Evidently we can expect a certain degree of variety in extrasolar planetary systems, even though Earth-like planets may nearly always be present.*[36]

Two Models for the Formation of a Giant Planet

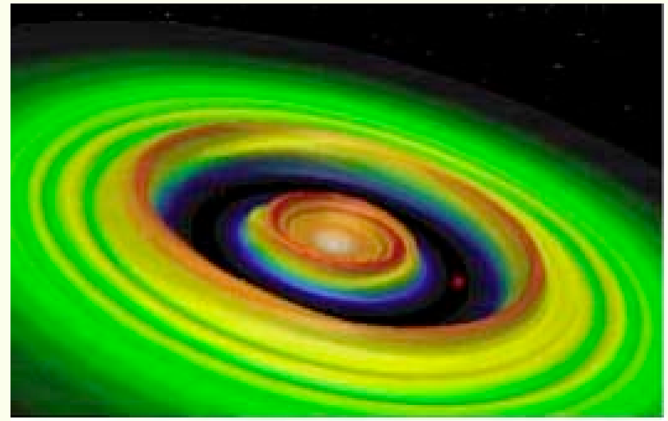
A, In the gravitational instability model for the formation of a giant planet, an unstable ring of gas developed in the solar nebula. A Jupiter-size mass within this ring collapsed under its own weight to form a giant planet. **B,** A second possibility is that the core of a Jovian planet formed first and then captured gas from the surrounding solar nebula.



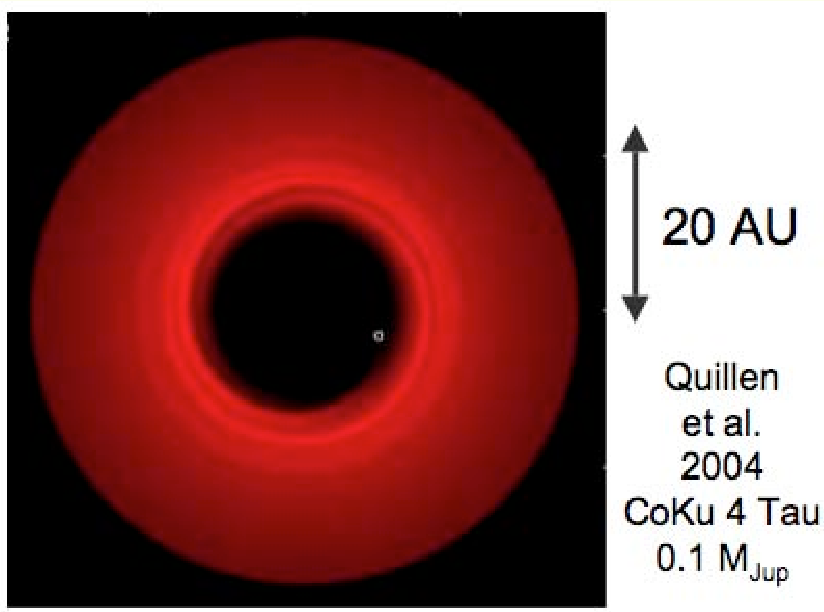
Three hydrodynamic simulations of formation of giant planets by gravitational instability and their effect on the disk. This suggests how observations of disks could be used to detect the presence of unseen planets!



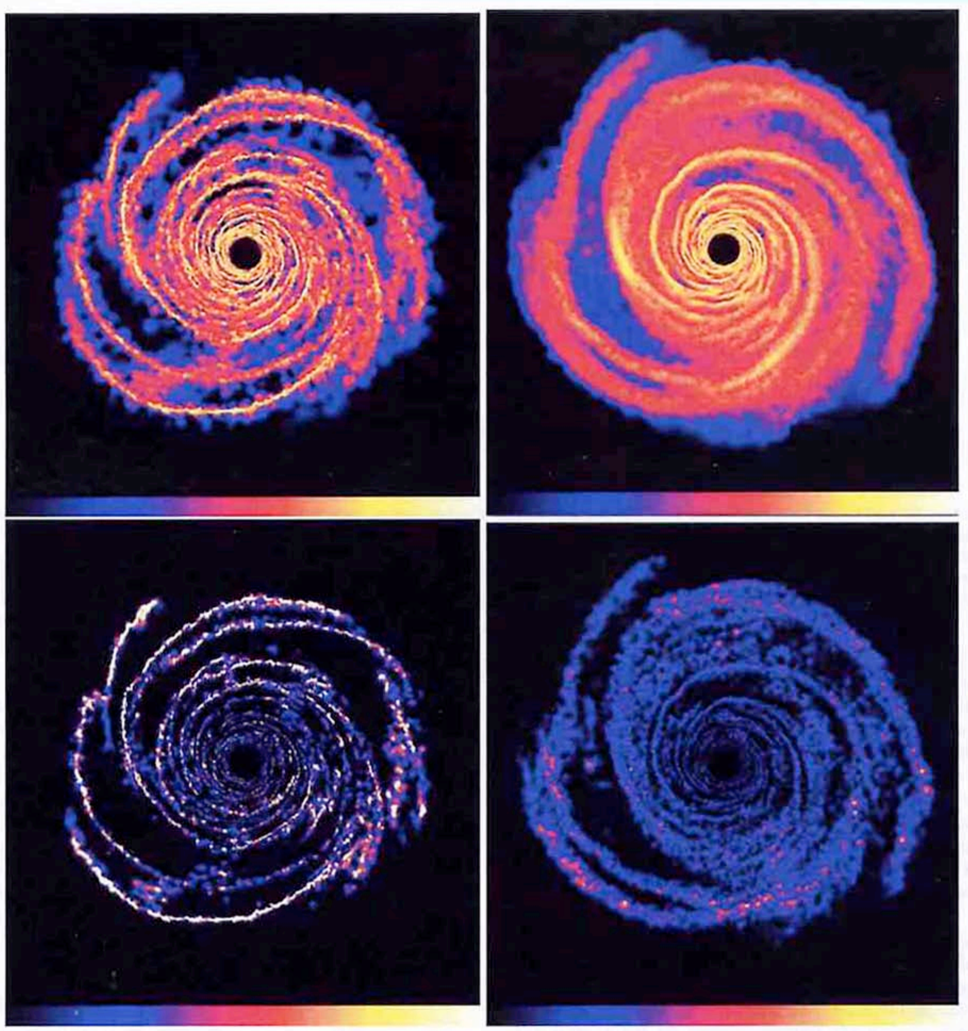
Quinn et al. 2004

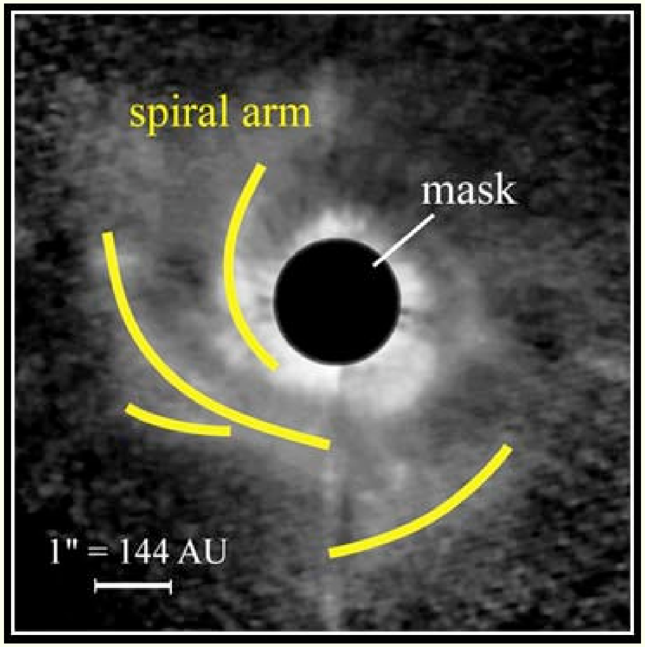


Bryden et al. 1999

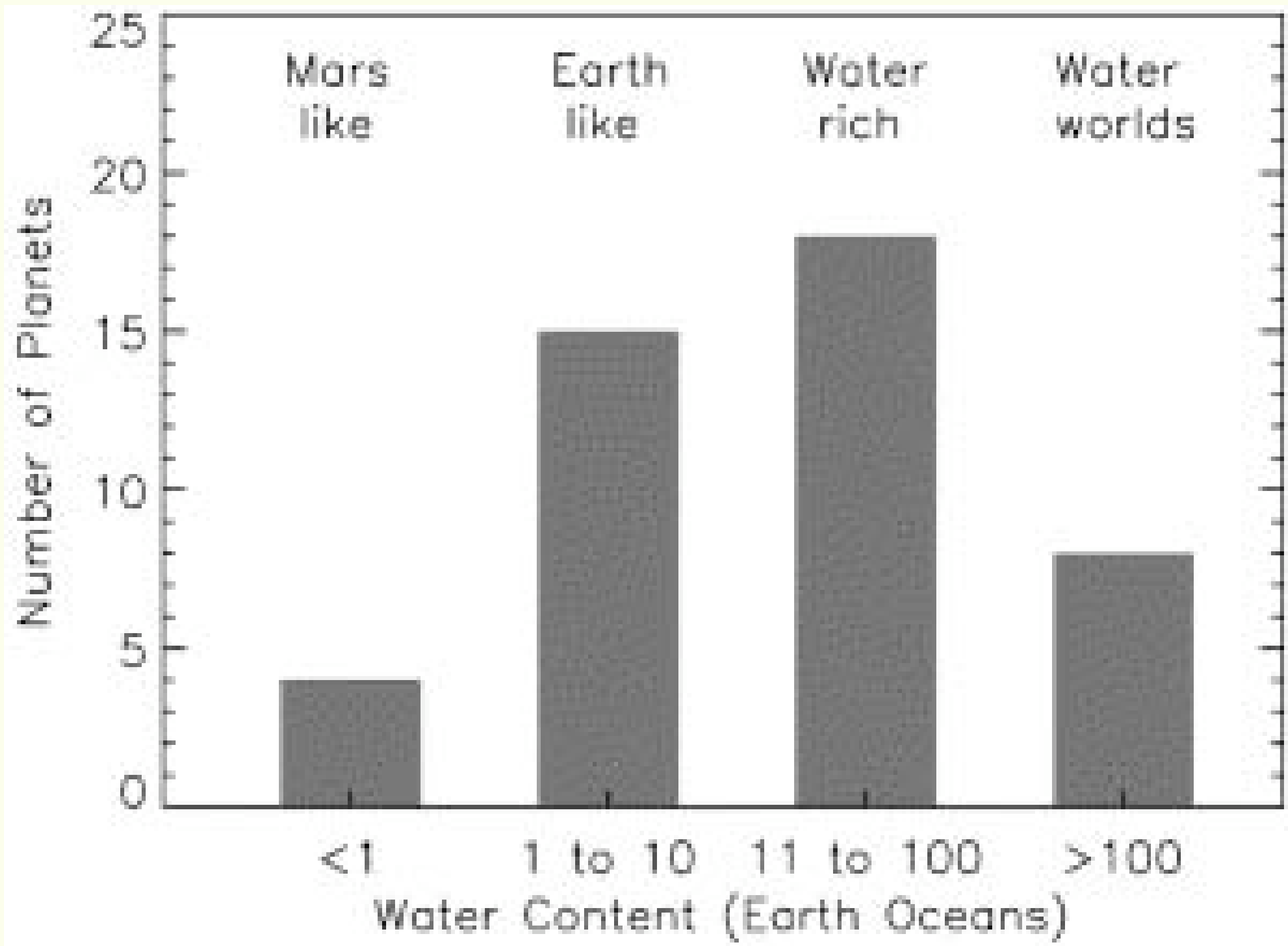


Gravitational instability of the disk might even assist in collisional planetesimal growth by concentrating the small particles (left: 50 cm, right: 100 cm) into spiral arms (Rice et al. 2004). Recall the observed IR image image of the disk around AB Aurigae (shown to right)

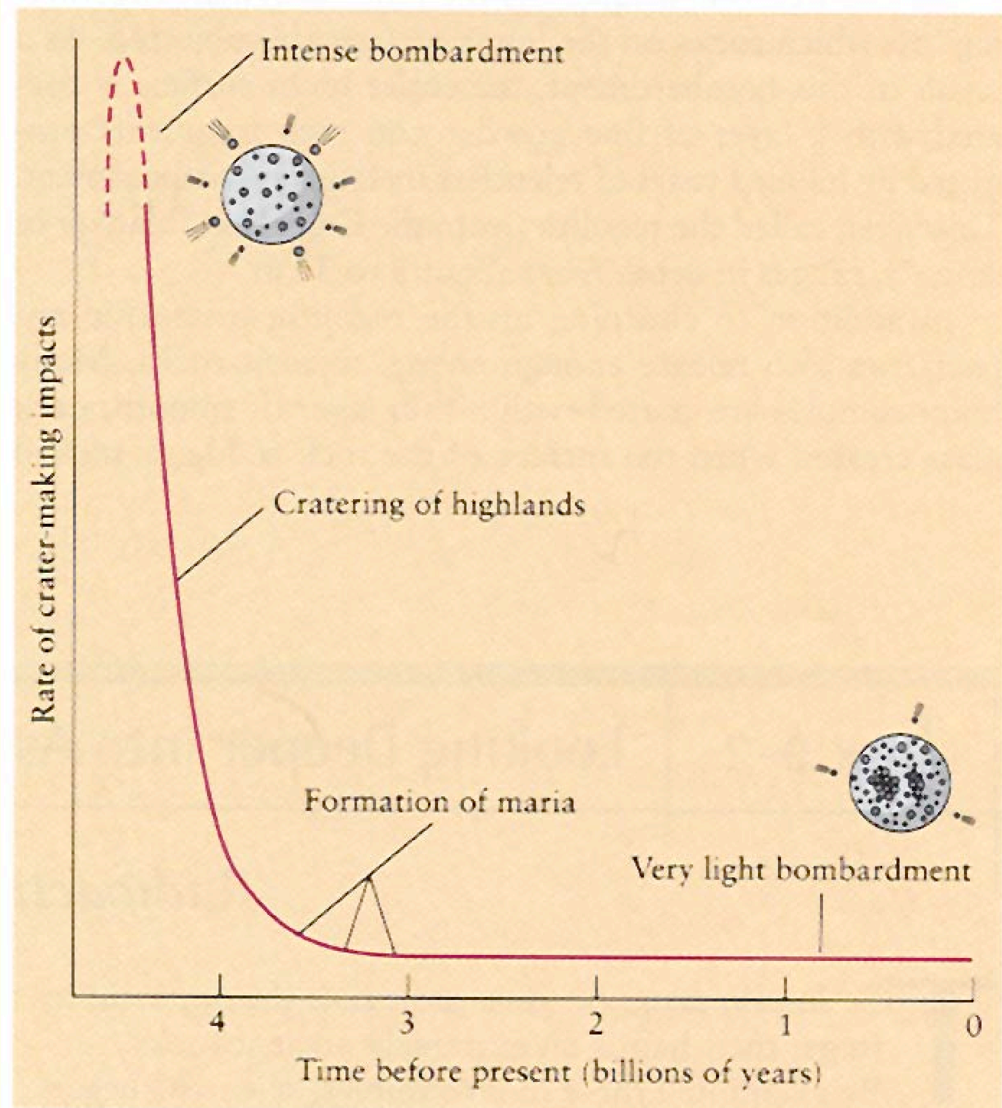




For 45 planets that formed in “habitable zone” in all 44 simulations, diagram shows fraction that ended up with various water contents. “Mars like” means less water than Earth, “Water worlds” have no continents but deep water mantles (Raymond et al. 2004).

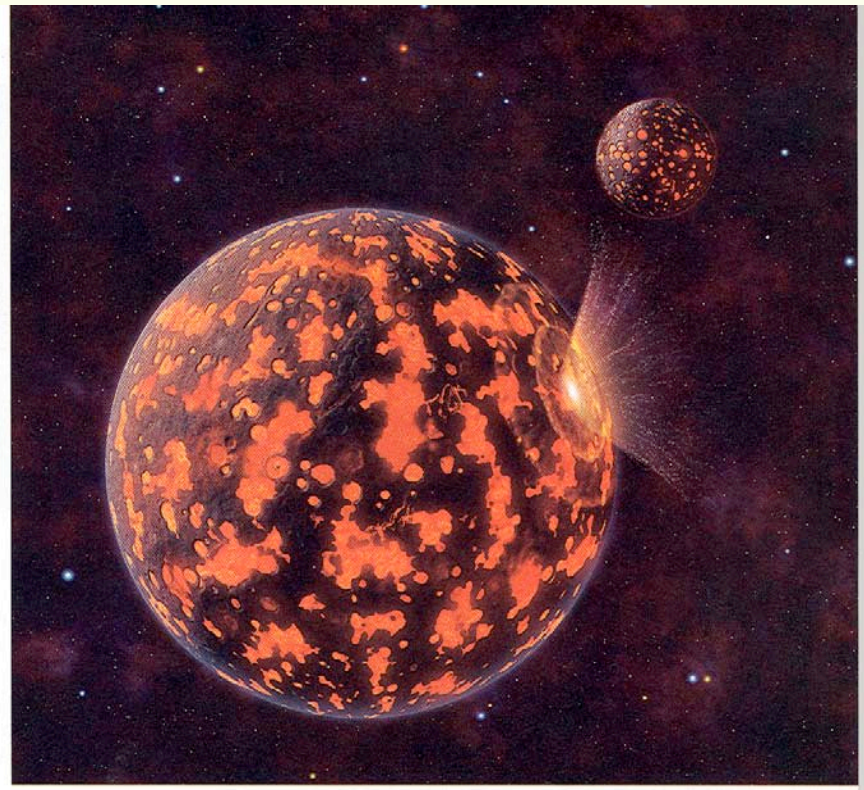


Even after the planets were formed, there was still a period of “heavy bombardment” by the remaining planetesimals. Here is the main evidence from the lunar cratering history.



The last stages of planet formation were undoubtedly dominated by violent collisions between planets and planetesimals in various phases of growth (left), resulting in a molten Earth (right), the formation of our Moon (discussed earlier), and the various peculiarities we observe in our solar system (see first slide)

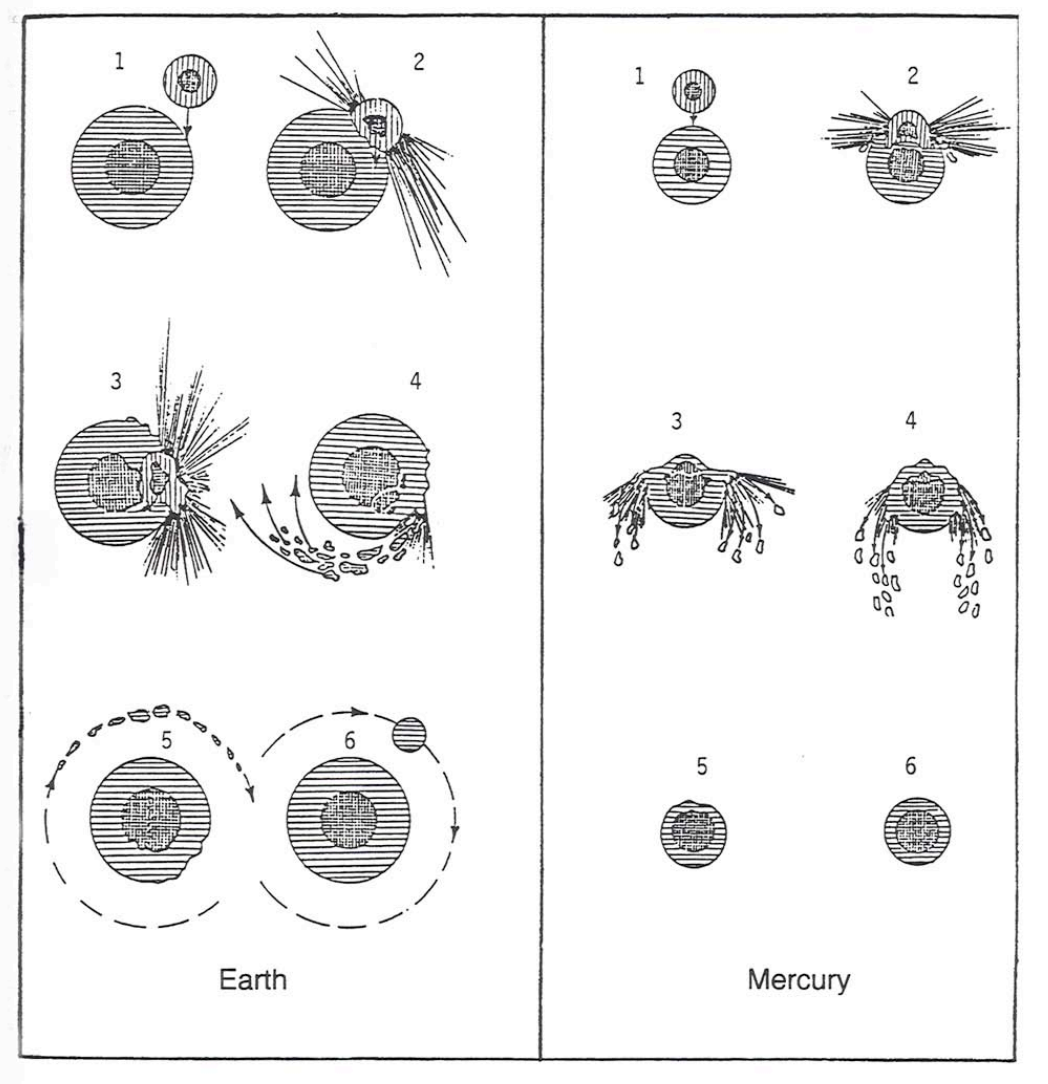
Collisions between planetesimals during the formative stages of the solar system. Many meteorites are fragments of these planetesimals, dating back to the origin of our planetary system. *(Painting by Don Dixon)*



Around 4 billion years ago, Earth, its Moon, and the other planets were heavily bombarded by leftover planetesimals. This painting shows the young Earth and Moon glowing with the heat of accretion, and an impact in progress on the Earth.

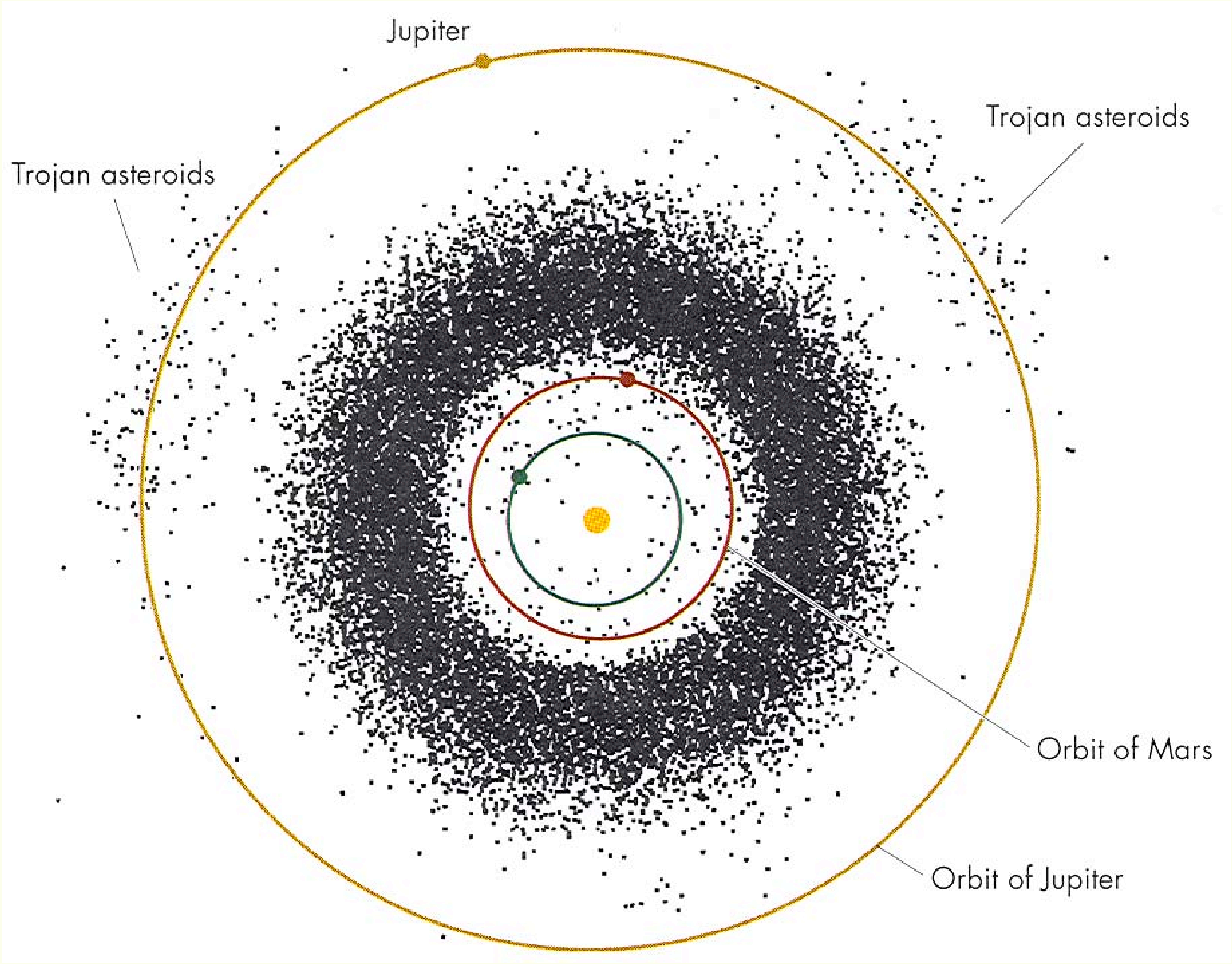
Earth-Moon (left): off-center collision removes part of Earth's mantle, but the matter becomes bound and coalesces into the Moon

Mercury (right): nearly head-on collision removes mantle (silicates) nearly completely, and lost from system, leaving iron-rich planet.

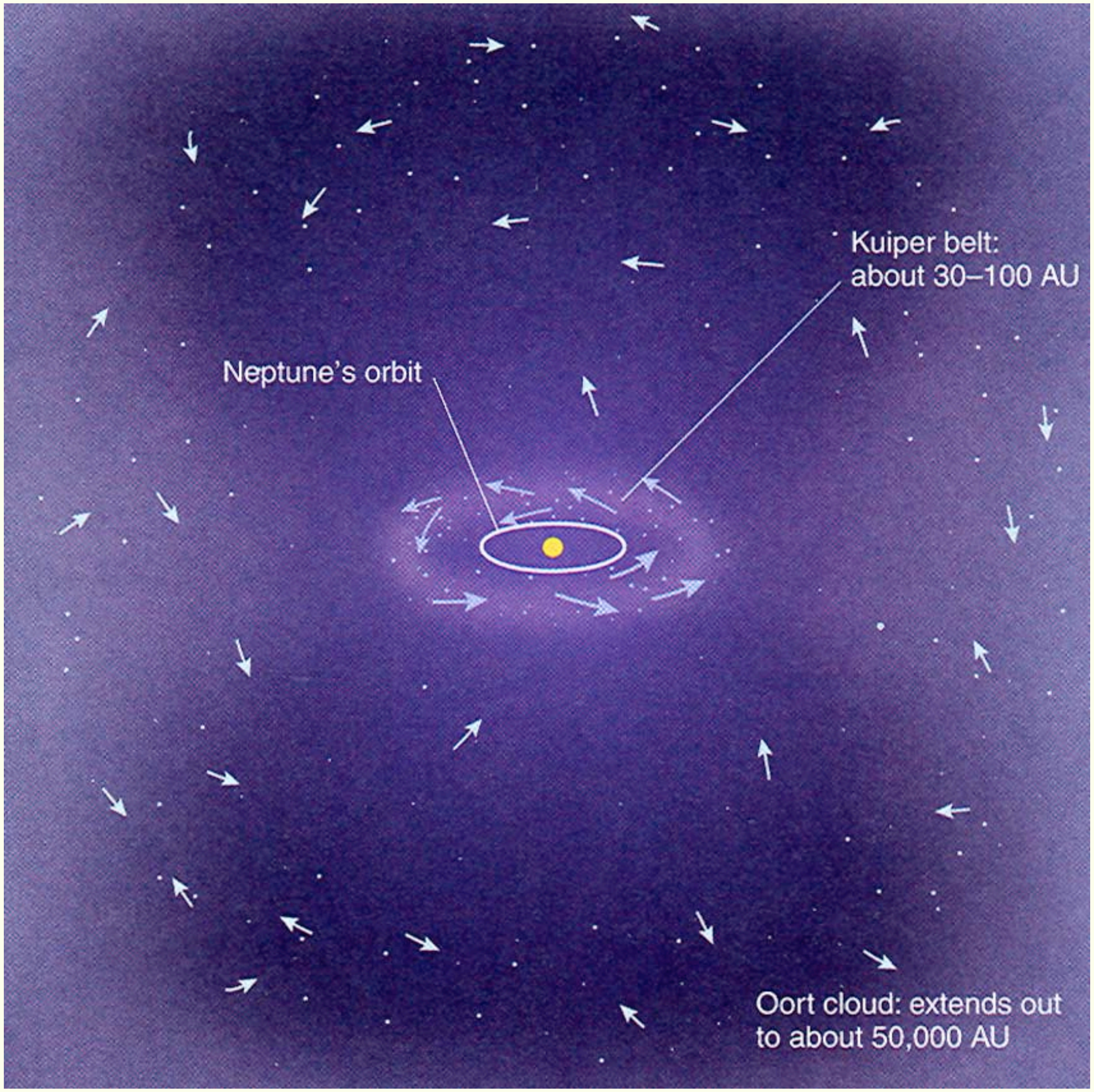


Results from the last stages of planetesimal collisions and scattering.

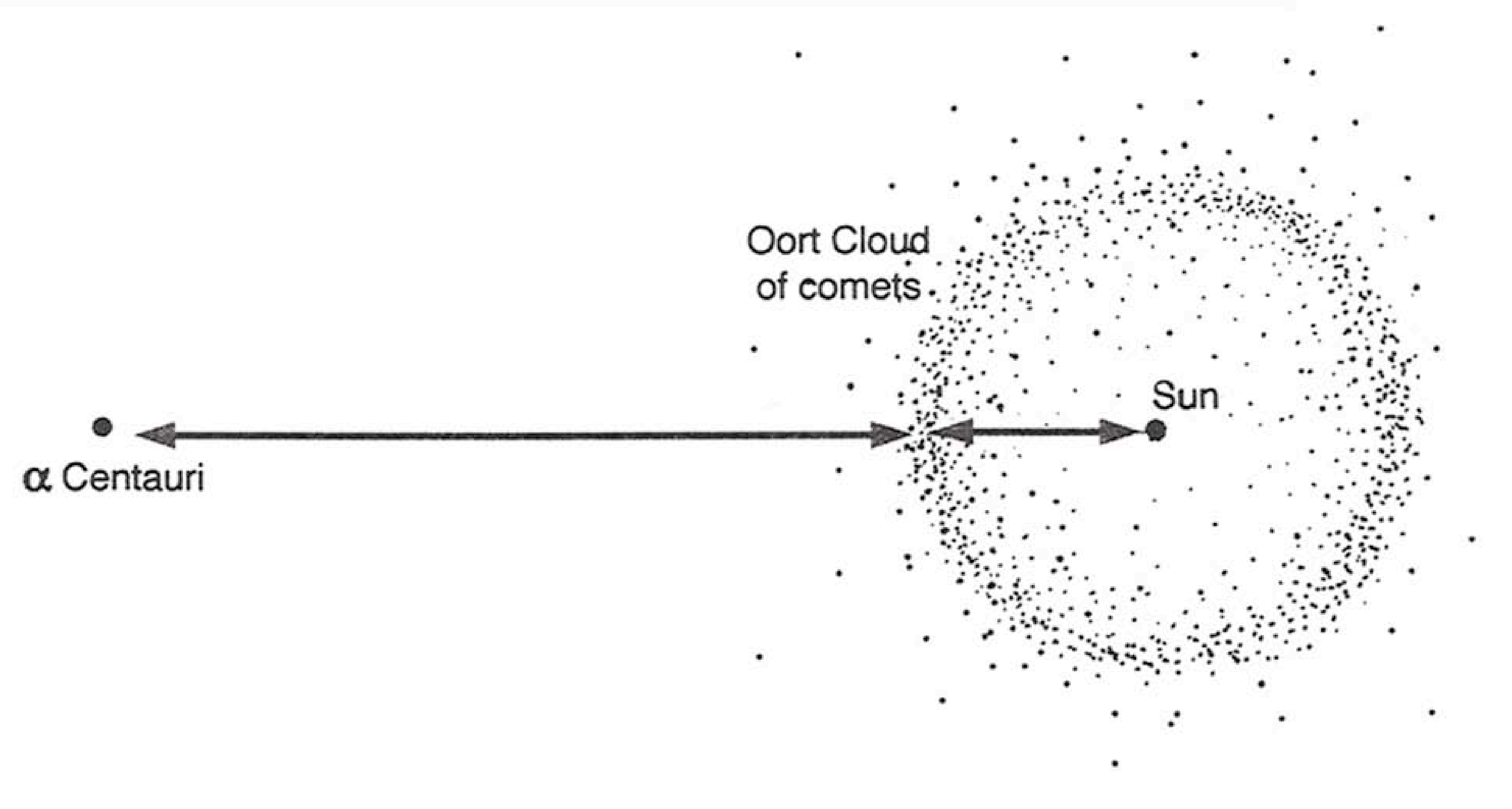
The asteroid belt: today only a small fraction of mass it once contained. Yet they still have important effects on life in the solar system.



Other planetesimals got scattered into either the **Kuiper belt** (observed), or the **Oort cloud** (inferred). We will see how important these may have been for life on Earth. Notice huge size of Oort cloud.



The extremely elongated orbits of Oort cloud comets keep them so far from the Sun that they are easily perturbed by passing stars, clouds, or even the tidal force of the rest of our Galaxy. That is why their rate of intrusion into the inner solar system can vary greatly (and lead to at least one mass extinction!)



Recent simulations including Jupiter present and water delivery (Raymond et al. 2004). This plot shows system at six times, color coded for water content. Note large final eccentricities and long time required to form final system (200 Myr).

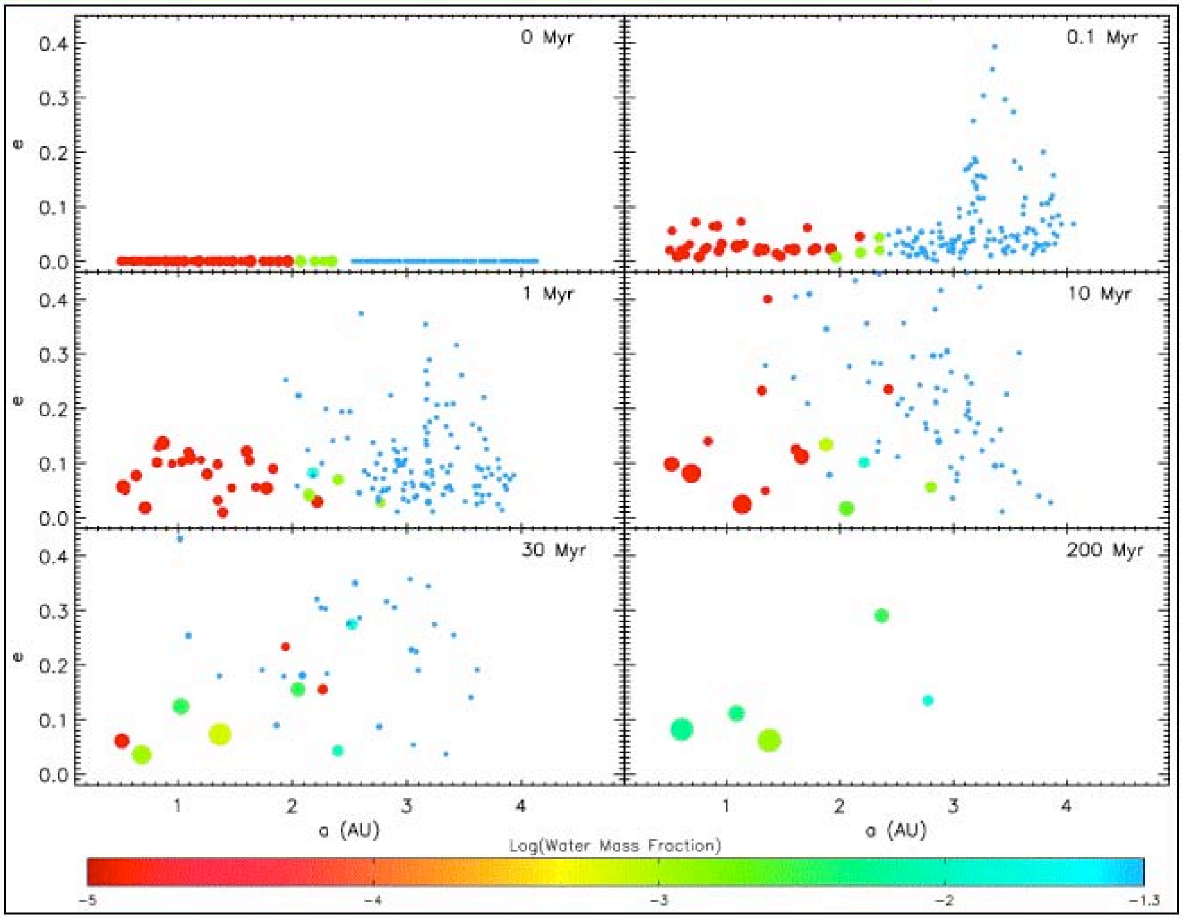


Fig. 3. Snapshots in the evolution of a simulation with Jupiter at 5.2 AU with zero eccentricity, and a planetesimal mass of $0.01 M_{\oplus}$ (simulation 10: see Table 1 for details). The size of each object is proportional to its mass$^{(1/3)}$ (but does not represent the actual physical size), and the color of each object corresponds to its water mass fraction. Note that the wettest objects have water mass fractions of $\log_{10}(5\%)$=-1.3. See text for discussion.

End results of nine (out of 44) simulations, showing effect of changing the assumed eccentricity of Jupiter's orbit (the vertical columns). Notice how number of planets and especially water content are affected. These simulations suggest that probability of planets having significant liquid water, even if in the "habitable zone," may be very sensitive to initial presence of giant planets and their properties.

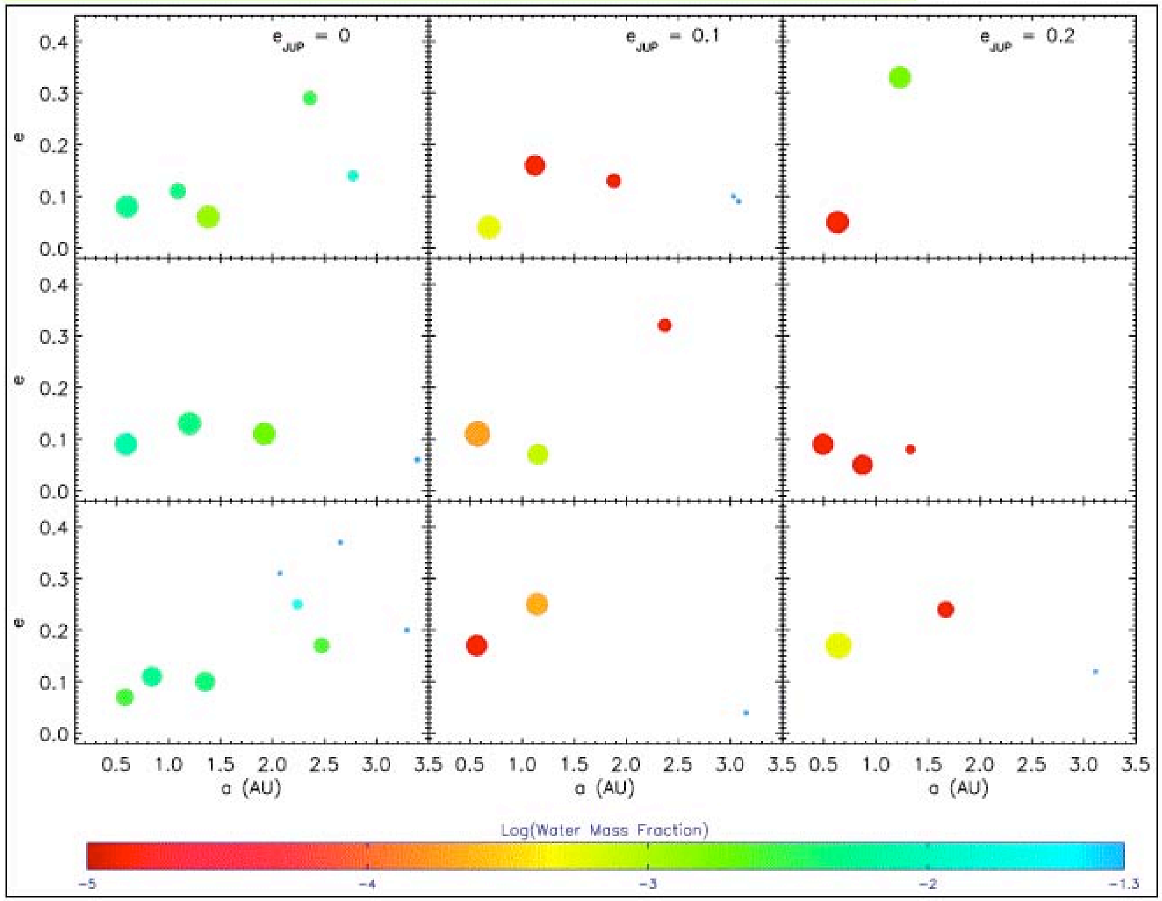


Fig. 6. The final configuration of nine planetary systems with identical initial conditions (a_J=5.2 AU, M_J=$M_{J,\odot}$, $M_{planetesimal}$=0.01$M_\oplus$) apart from Jupiter's initial eccentricity, which is the same for all simulations in a given column. Note the dramatic decline in volatile content for e_J greater than zero.

Eleven simulation cases that formed a planet ~ 1 AU for different initial conditions and Jupiter properties, allowing for “exogenous delivery” of water by icy planetesimals.. Solar system is shown for comparison in lower right. Notice large variation in water content--other “Earths might be much different than ours.

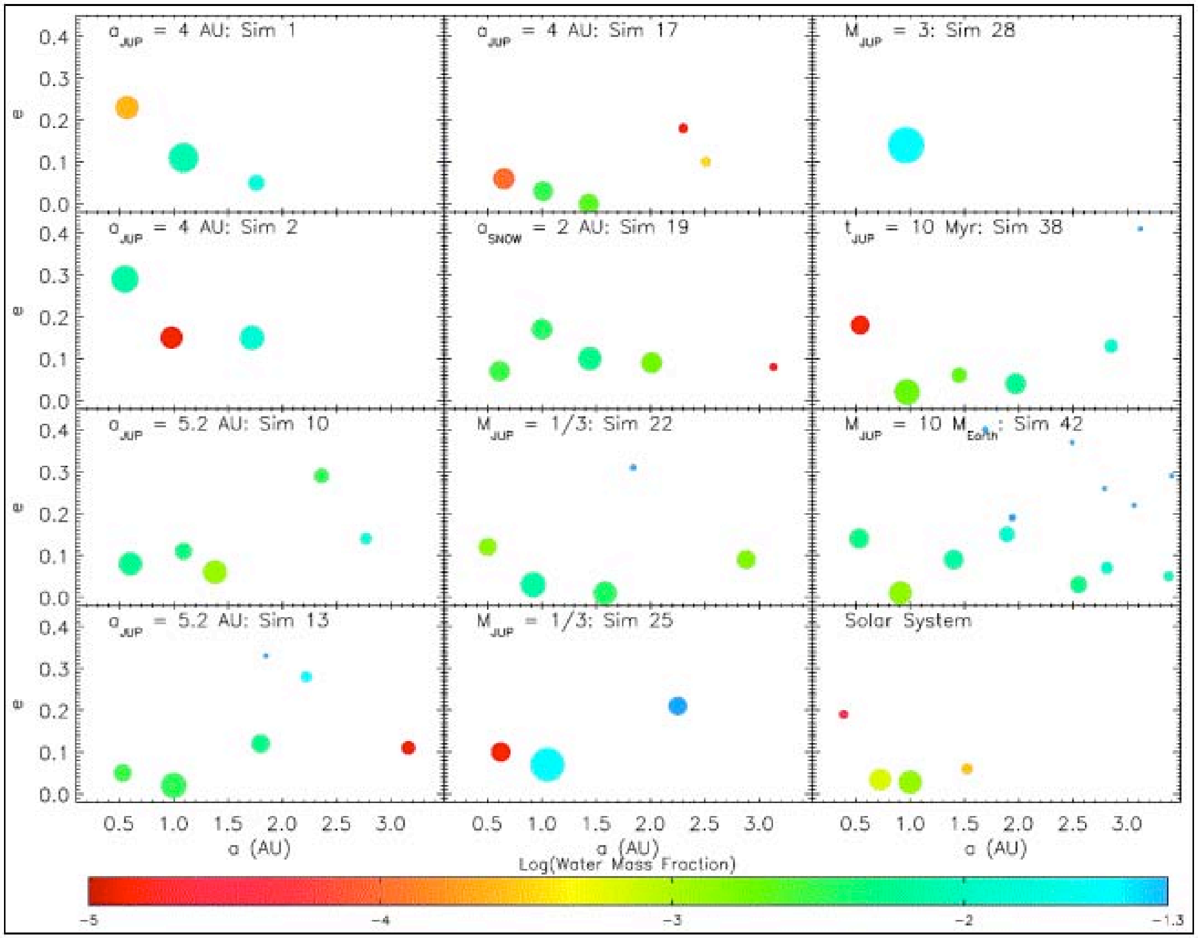


Fig. 8. Final configuration of 11 simulations which formed a "habitable" planet with 0.9 AU<a<1.1 AU, labeled by the physical parameters of each planetary system and the simulation number. If not otherwise mentioned, $M_J = M_{J,\prime}$ and $e_J=0$. Our Solar System is included for comparison, with 3 Myr averaged values from [Quinn et al., 1991]. See Table 1 and Table 2 for more details.