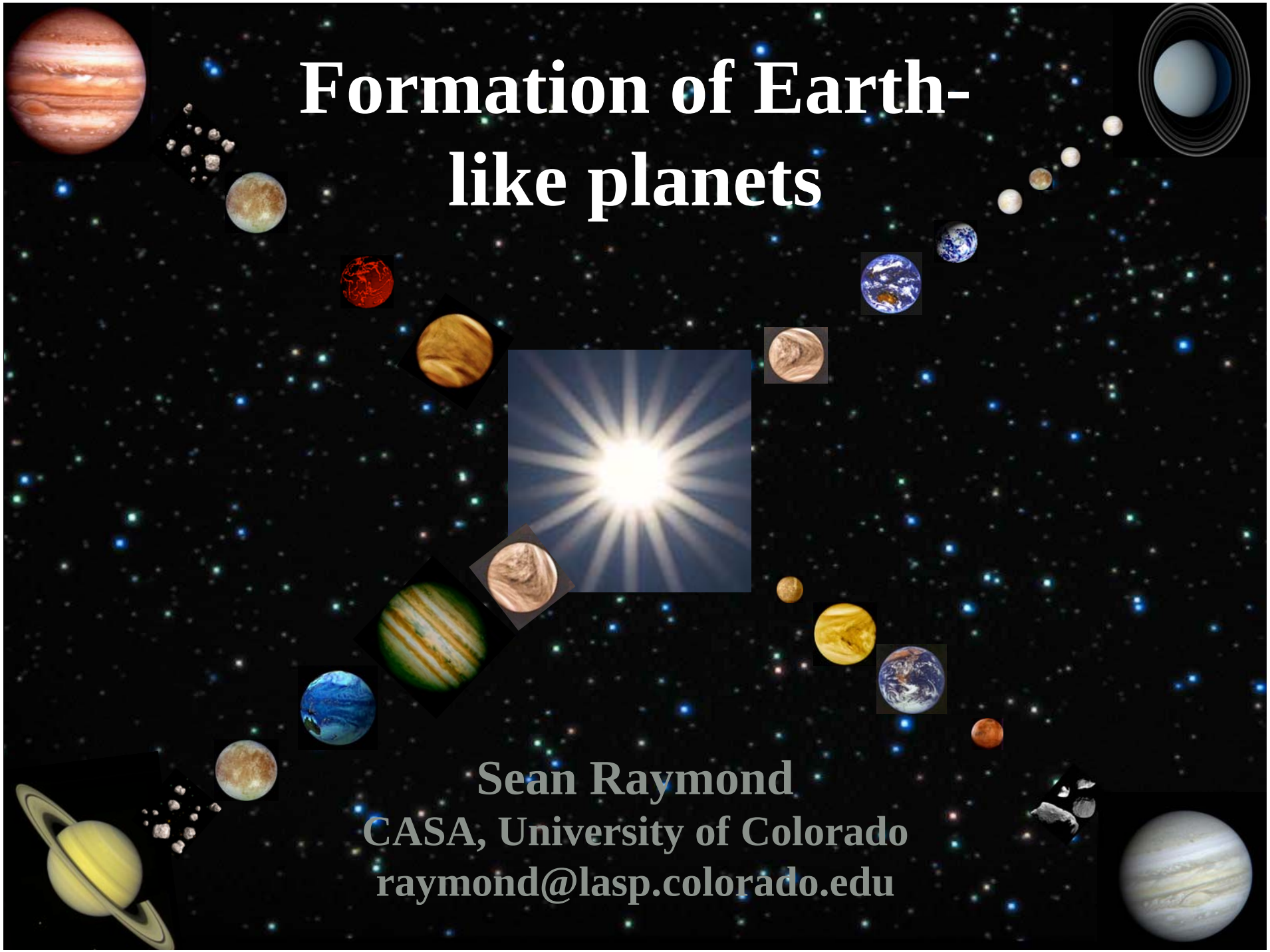
Formation of Earth-like planets



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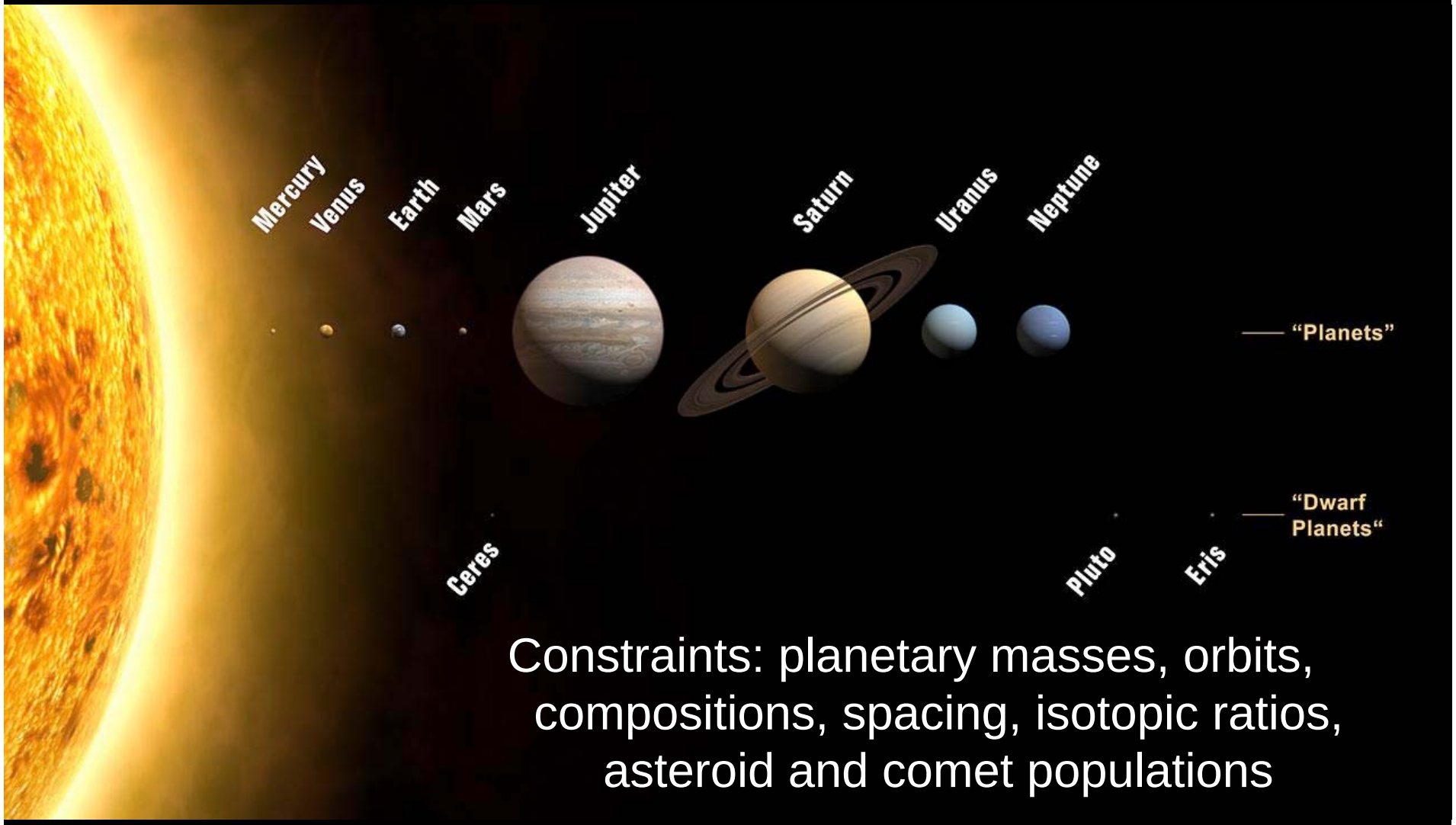
How do terrestrial planets like the Earth form?

Where conditions are required to form Earth-like planets?

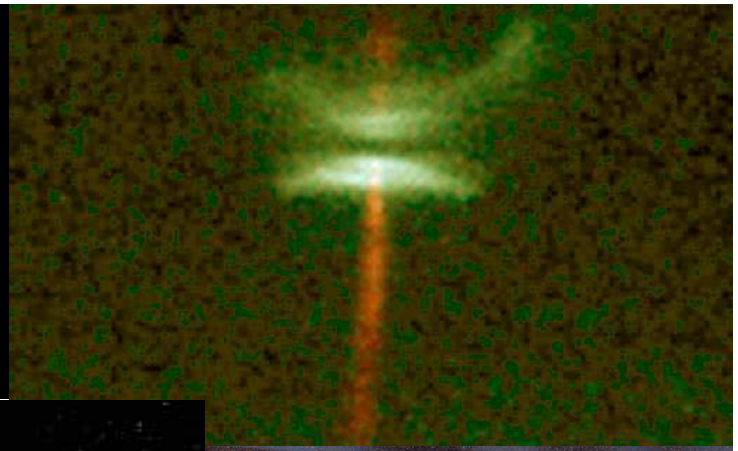
What is the diversity of terrestrial planets that can form?

The (new) Solar System planets

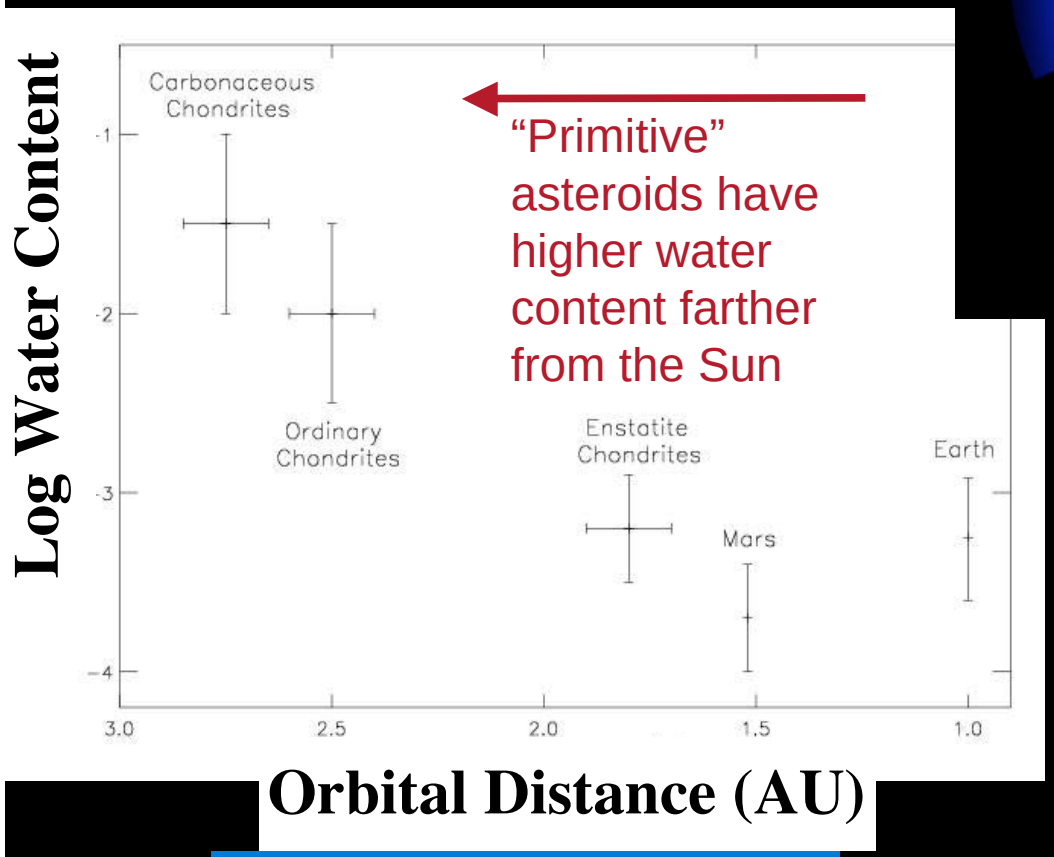


Constraints: planetary masses, orbits, compositions, spacing, isotopic ratios, asteroid and comet populations

Planets form in disks around stars

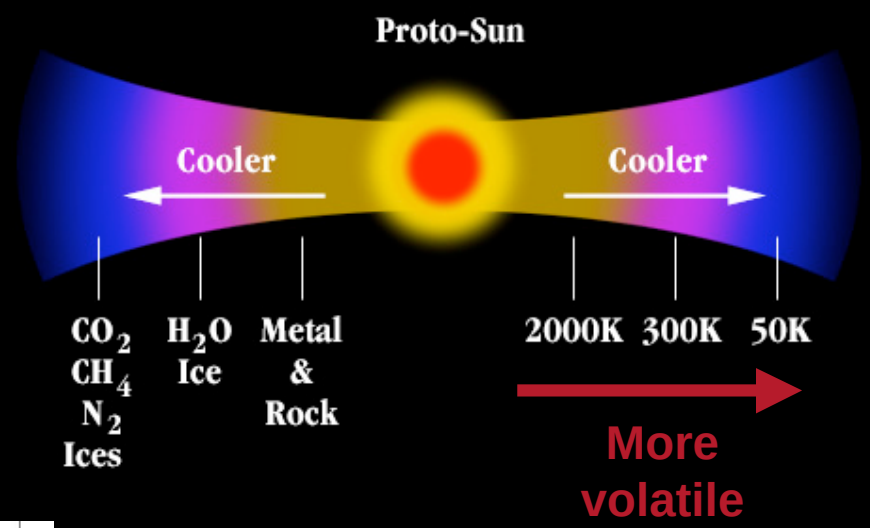


The Solar Nebula



"Primitive" asteroids have higher water content farther from the Sun

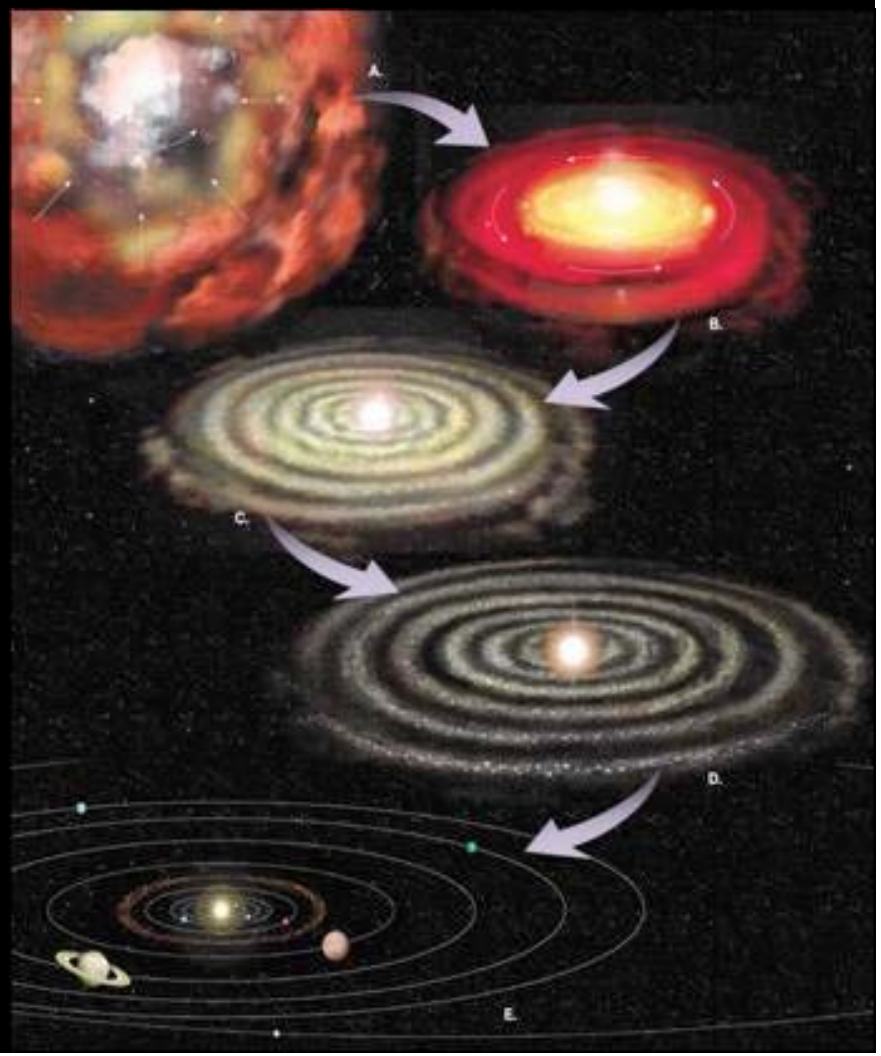
Raymond, Quinn & Lunine 2004; based on Abe et al 2000



Disk temperature profile imprinted on primitive bodies

Sequence of Events in Solar System Formation

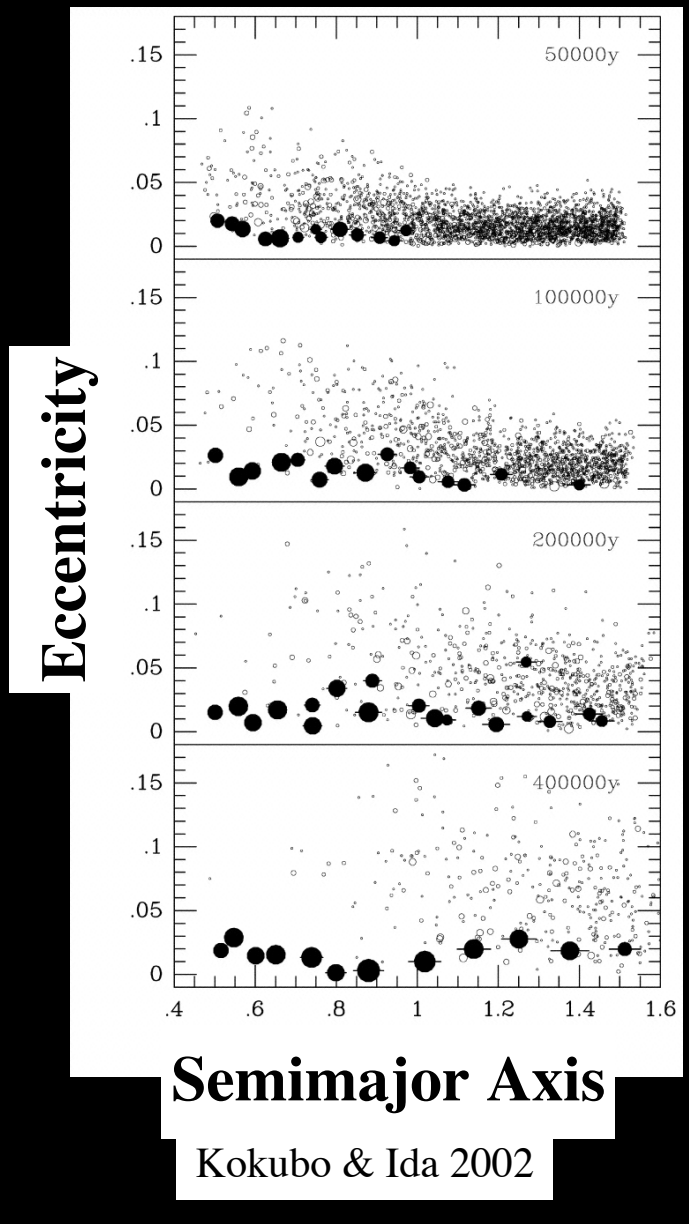
1. Collapse of Sun and Solar Nebula
2. Formation of giant planets
   - Continued growth of terrestrial bodies
3. Dispersal of gas in disk (10^{6-7} years)
4. Final assembly of terrestrial planets (30-50 Myr)
5. Continued dynamical evolution of planetary system, impacts from asteroids and comets



Stages of Terrestrial Planet Formation

1. Grains condense in Solar Nebula and settle to the disk midplane (~10^{4-5} yrs)
2. ~1km "planetesimals" form (~10^5 yrs)
3. Runaway and Oligarchic Growth: Formation of ~Moon-Mars sized "Planetary Embryos" (~10^{5-7} yrs)
4. **Late-stage Accretion of terrestrial planets from embryos (~10^{7-8} yrs)**

(Giant planets form in <1-10 Myr, so they affect stages 3 and 4)



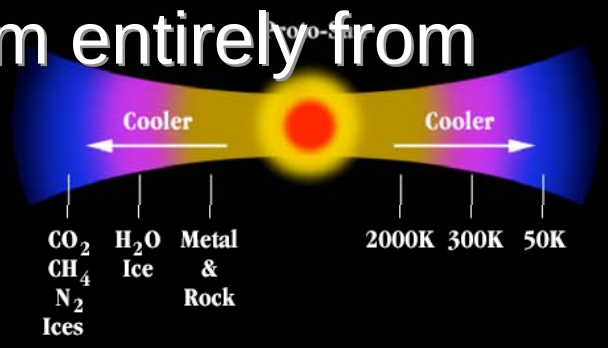
Kokubo & Ida 2002

Reviews: Lissauer 1993, Chambers 2004

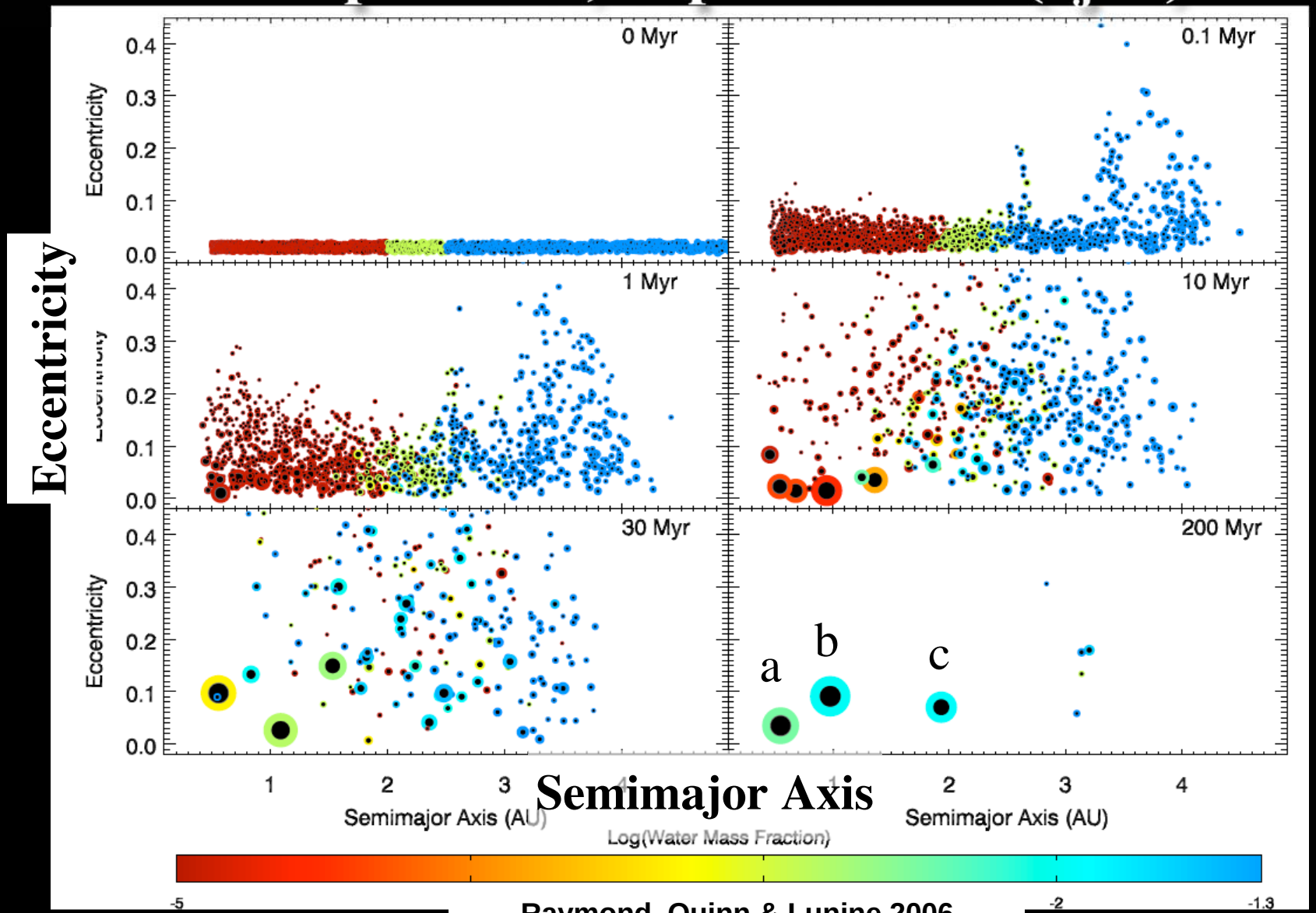
Where did Earth get its water?

- Earth is in the “habitable zone”, where water is liquid (hotter than 273 K = 0˚ C = 32˚ F)
- To incorporate water into Earth need icy impacts. Water freezes at 170 K (= -100˚ C = -150˚ F)

→Some of Earth’s building blocks came from past the “snow line”: Earth did not form entirely from local material (Morbidelli et al 2000)

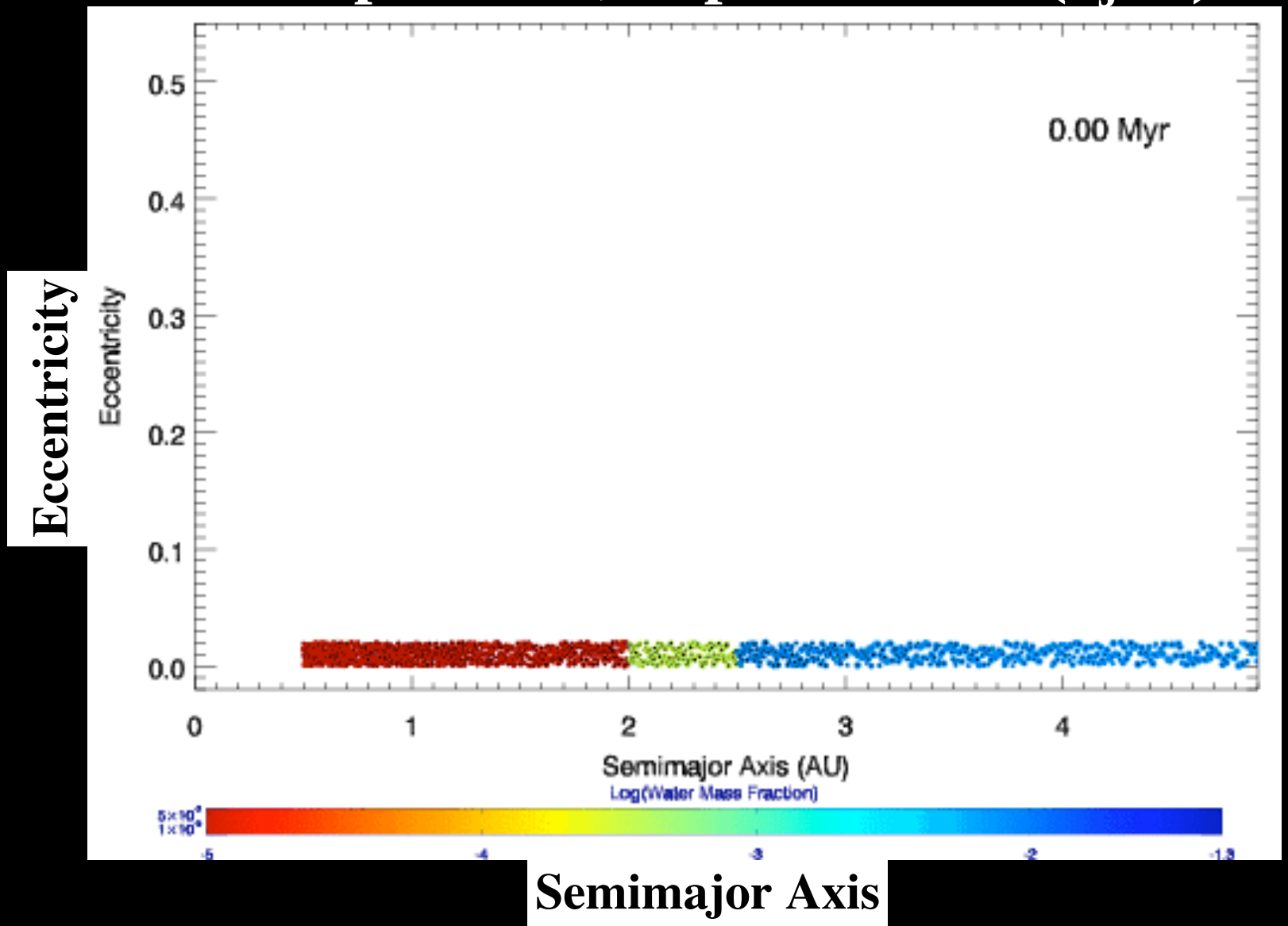


Snapshots in time of a high-res simulation: 1885 initial particles, Jup at 5.5 AU (e_J=0)



Raymond, Quinn & Lunine 2006

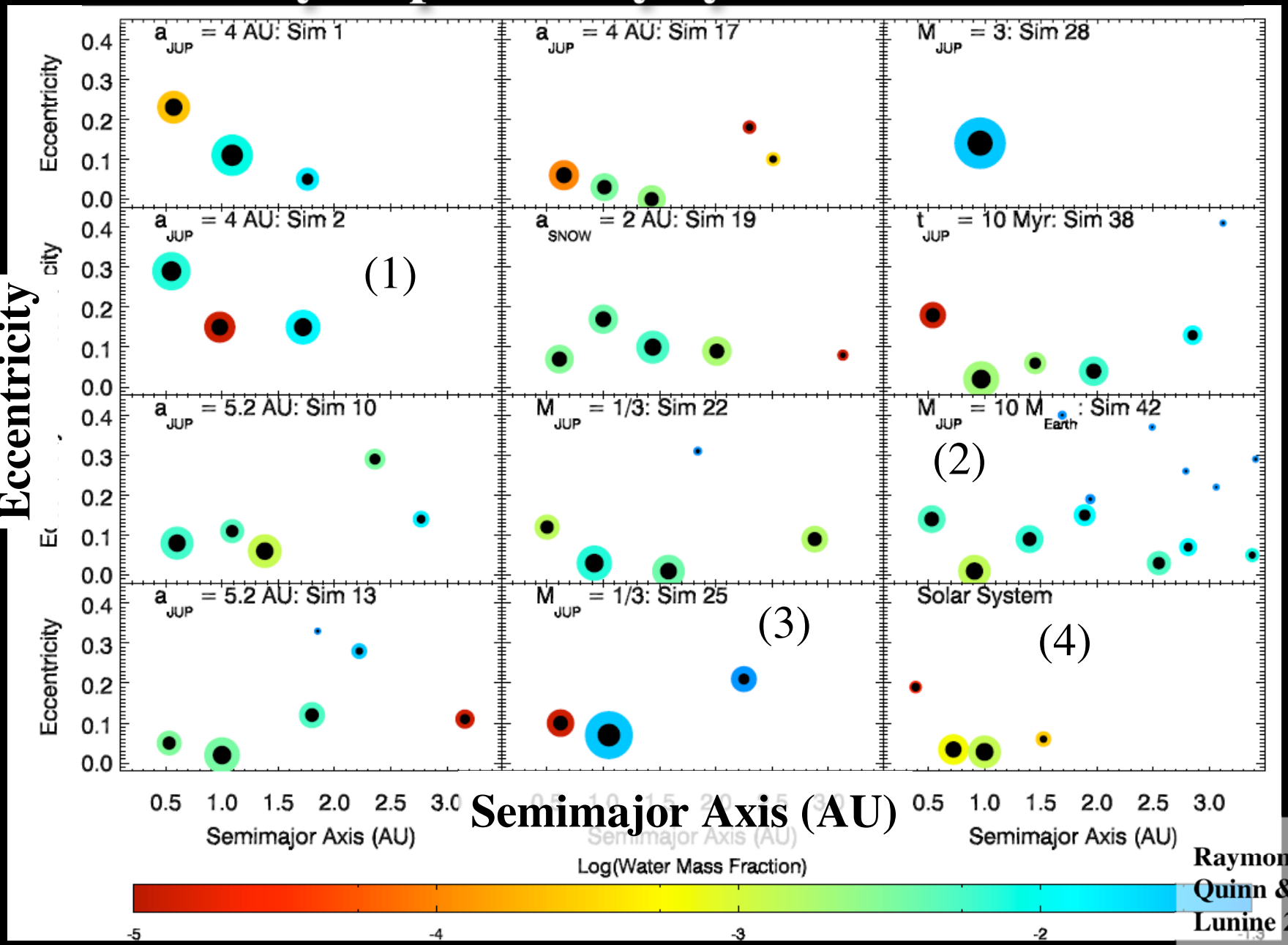
Evolution of a high-res simulation: 1885 initial particles, Jup at 5.5 AU (e_J=0)



Semimajor Axis

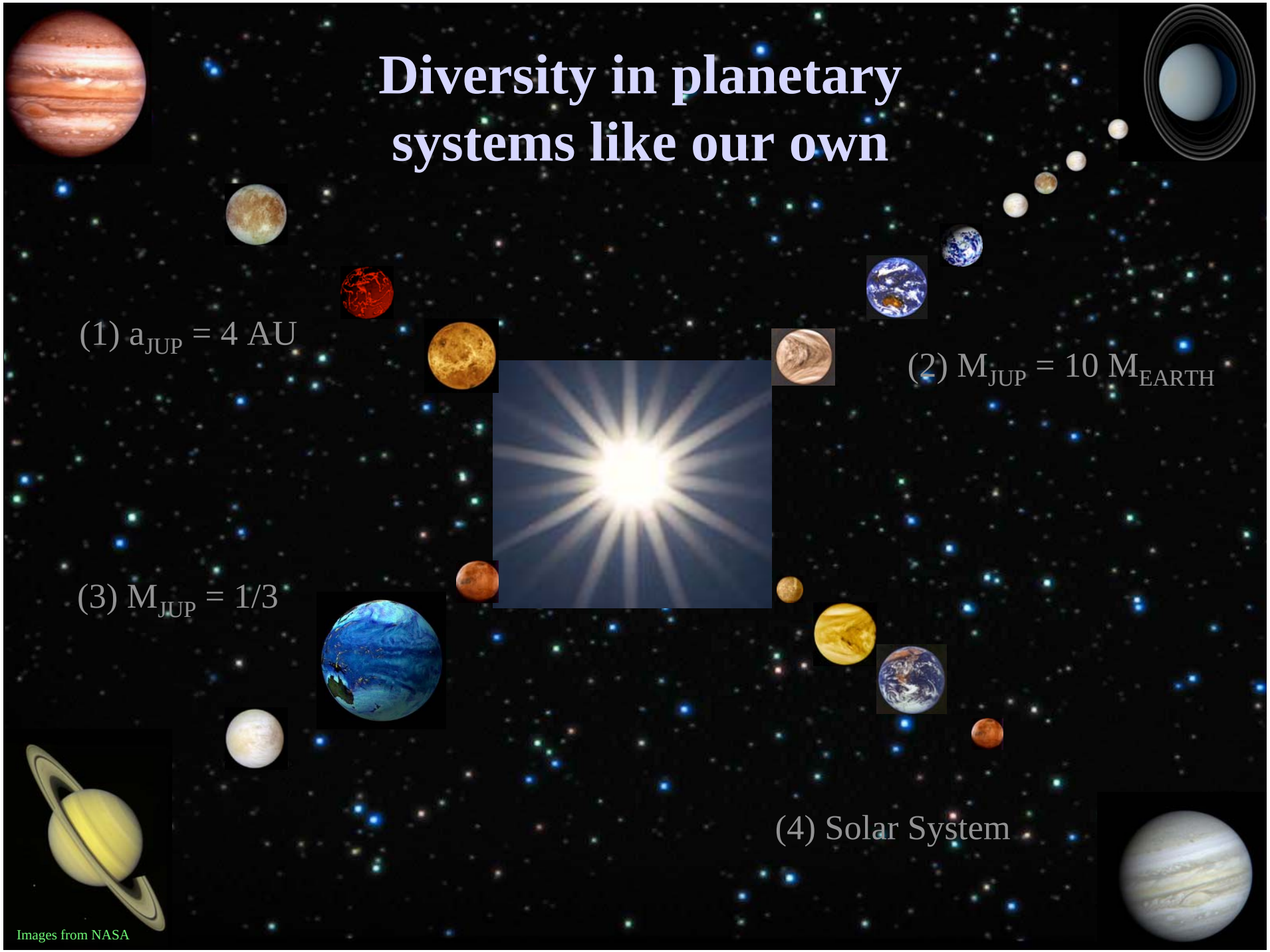
Raymond, Quinn & Lunine 2006

Diversity in planetary systems like our own



Raymond, Quinn & Lunine 2004

Diversity in planetary systems like our own

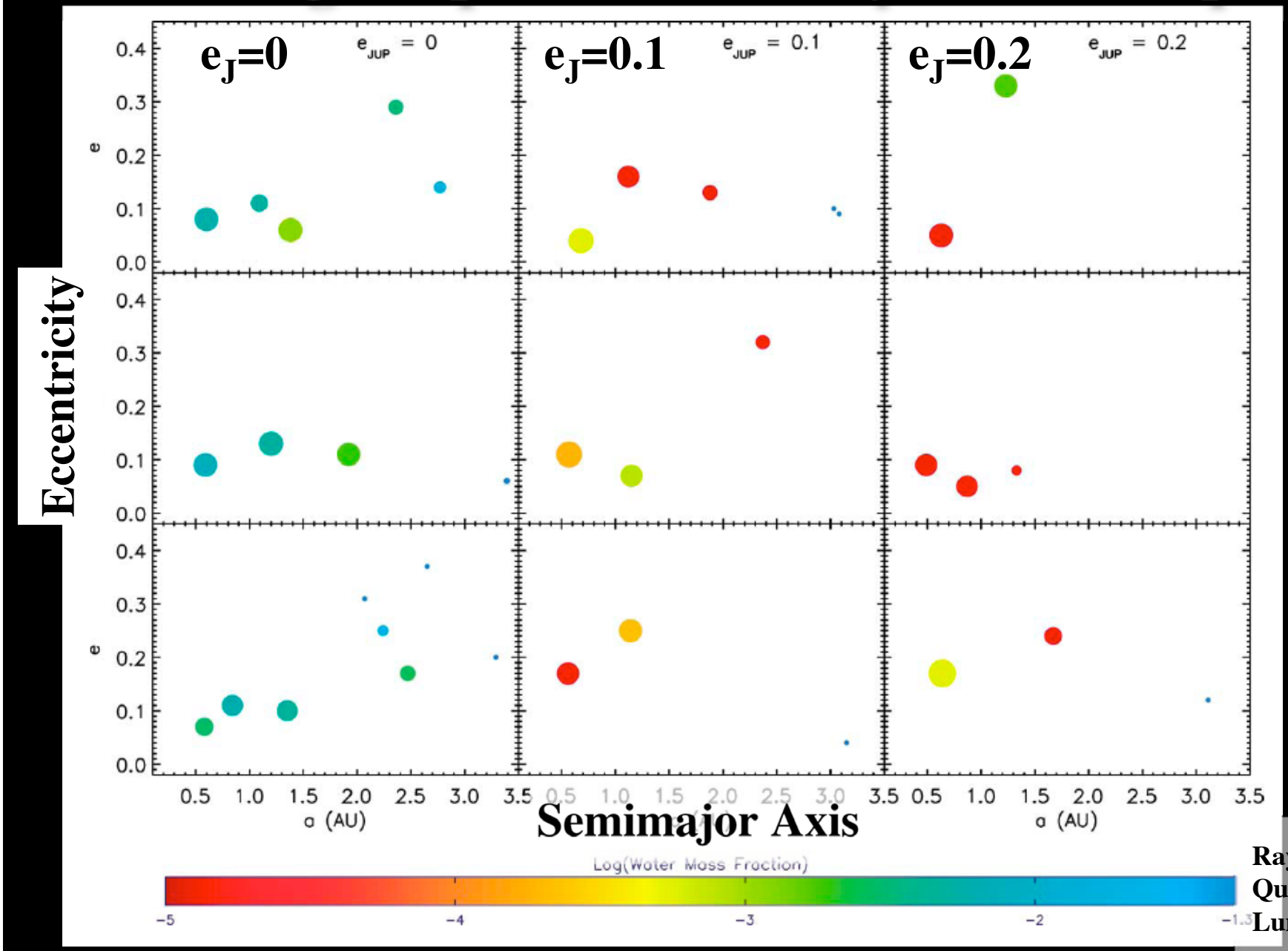


Images from NASA

Differences in Planetary Systems come from Two Sources

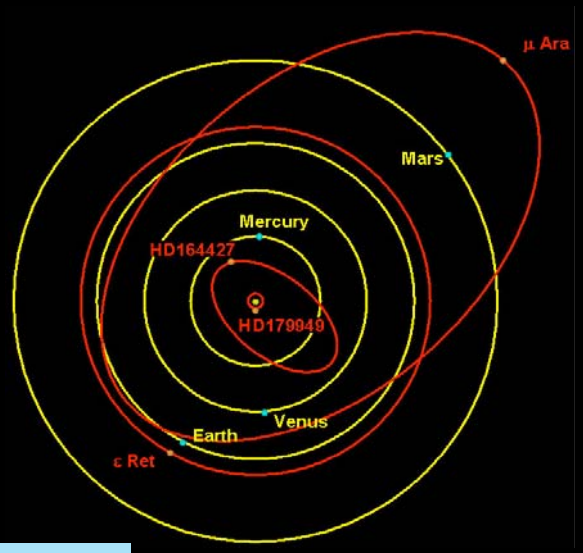
1. Stochastic variation in the accretion process because of the small number of embryos in late stages
2. Systematic variations among systems
   - Number, masses, orbits of giant planets
     - Higher $e_{JUP} \Rightarrow$ fewer, drier terrestrial planets
     - Higher $M_{JUP} \Rightarrow$ fewer, more massive terrestrial planets
   - Disk mass (related to stellar metallicity), disk surface density profile

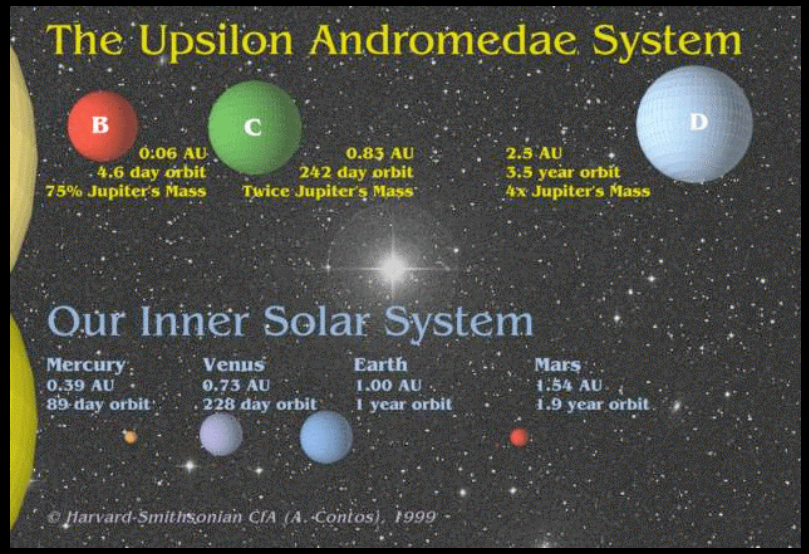
Eccentric giant planets form dry terrestrial planets



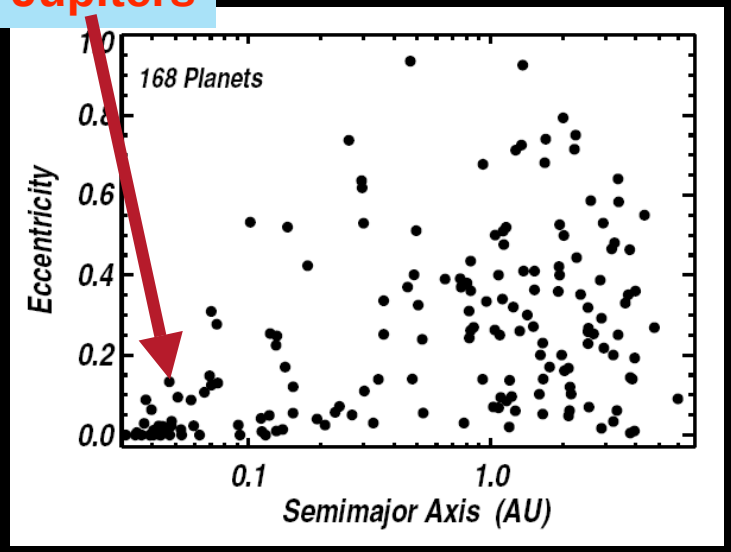
Raymond, Quinn & Lunine 2004

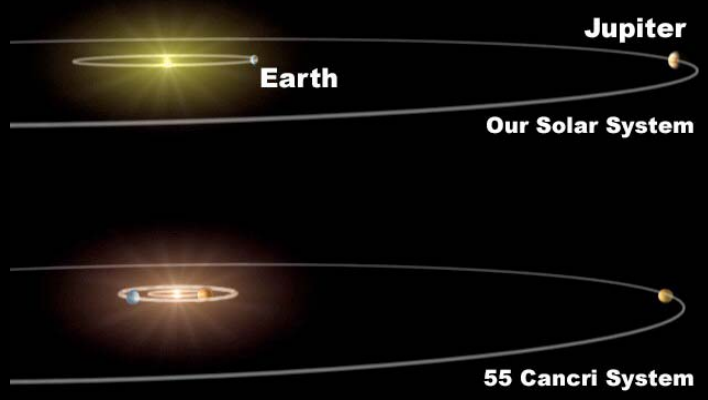
Could terrestrial planets exist in the known systems of extra-solar (giant) planets?





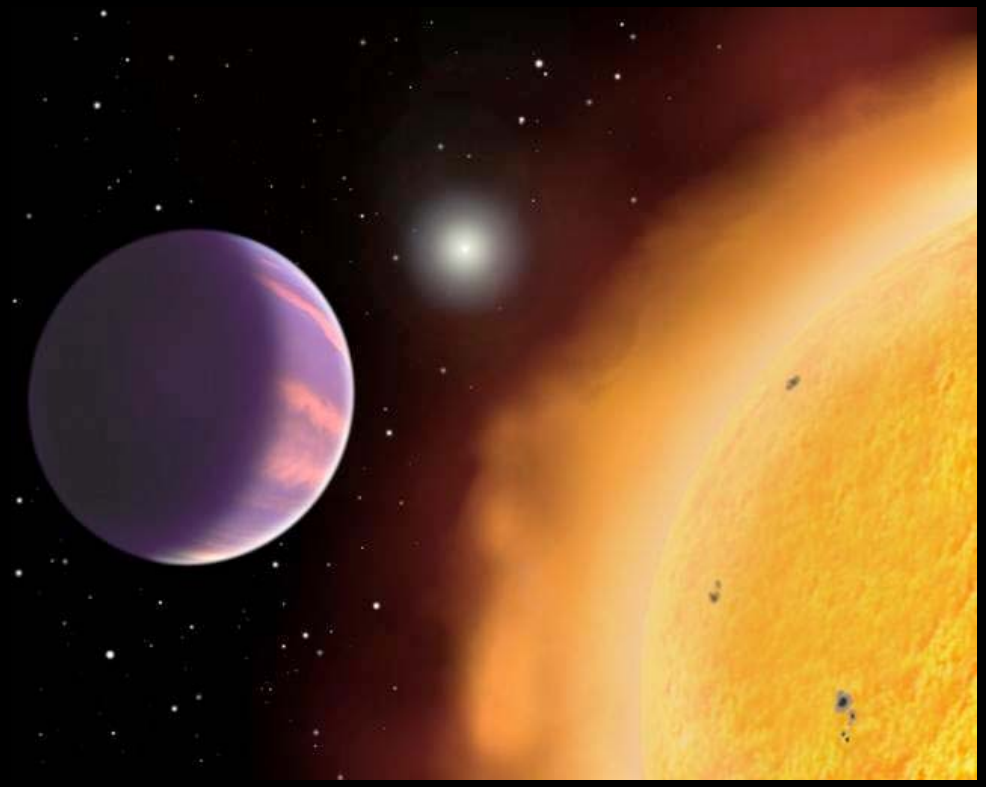
Hot Jupiters

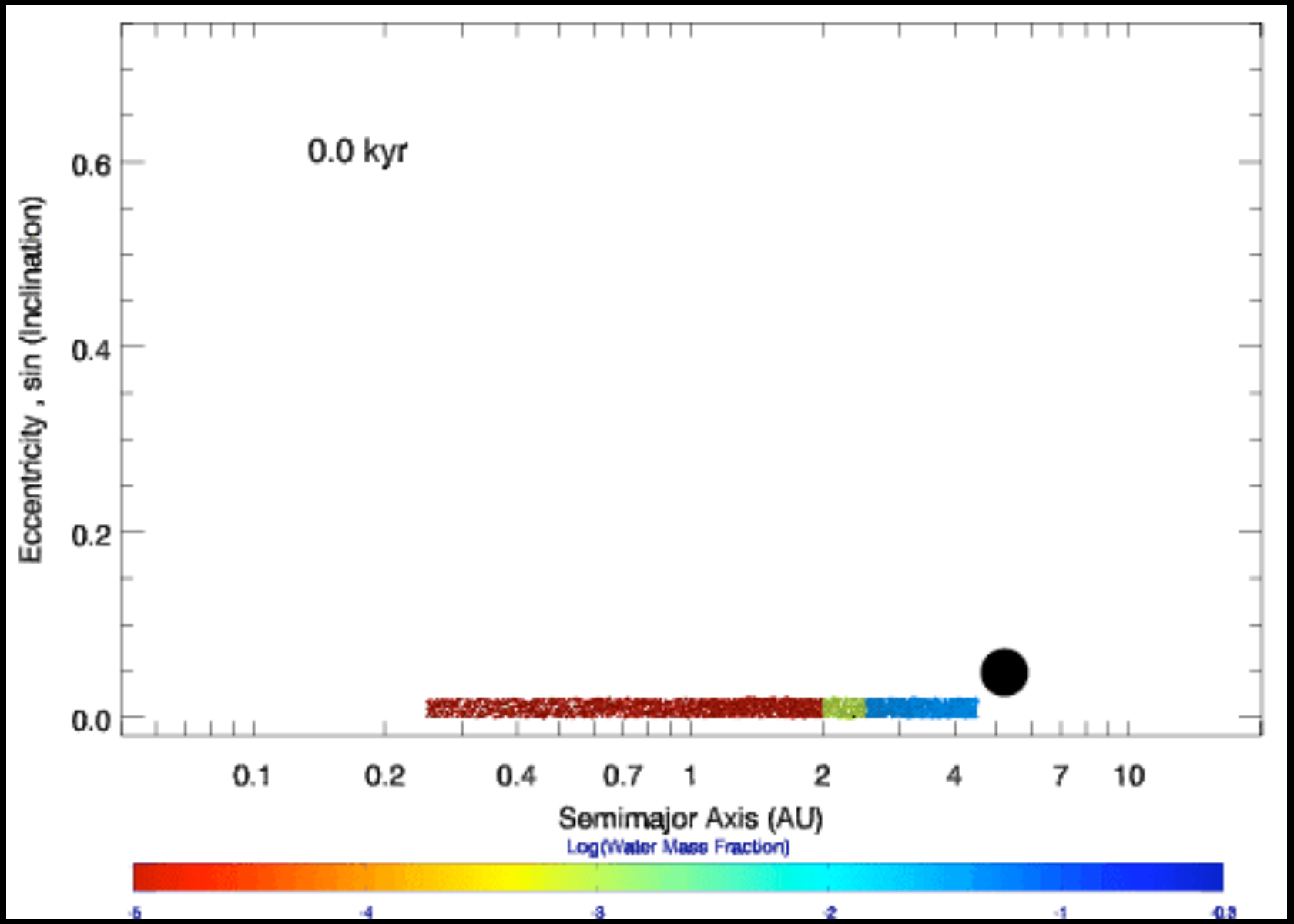




Giant Planet Migration

Hot Jupiters migrated to their current locations because of interactions with the protoplanetary disk. How does this affect terrestrial planet formation?

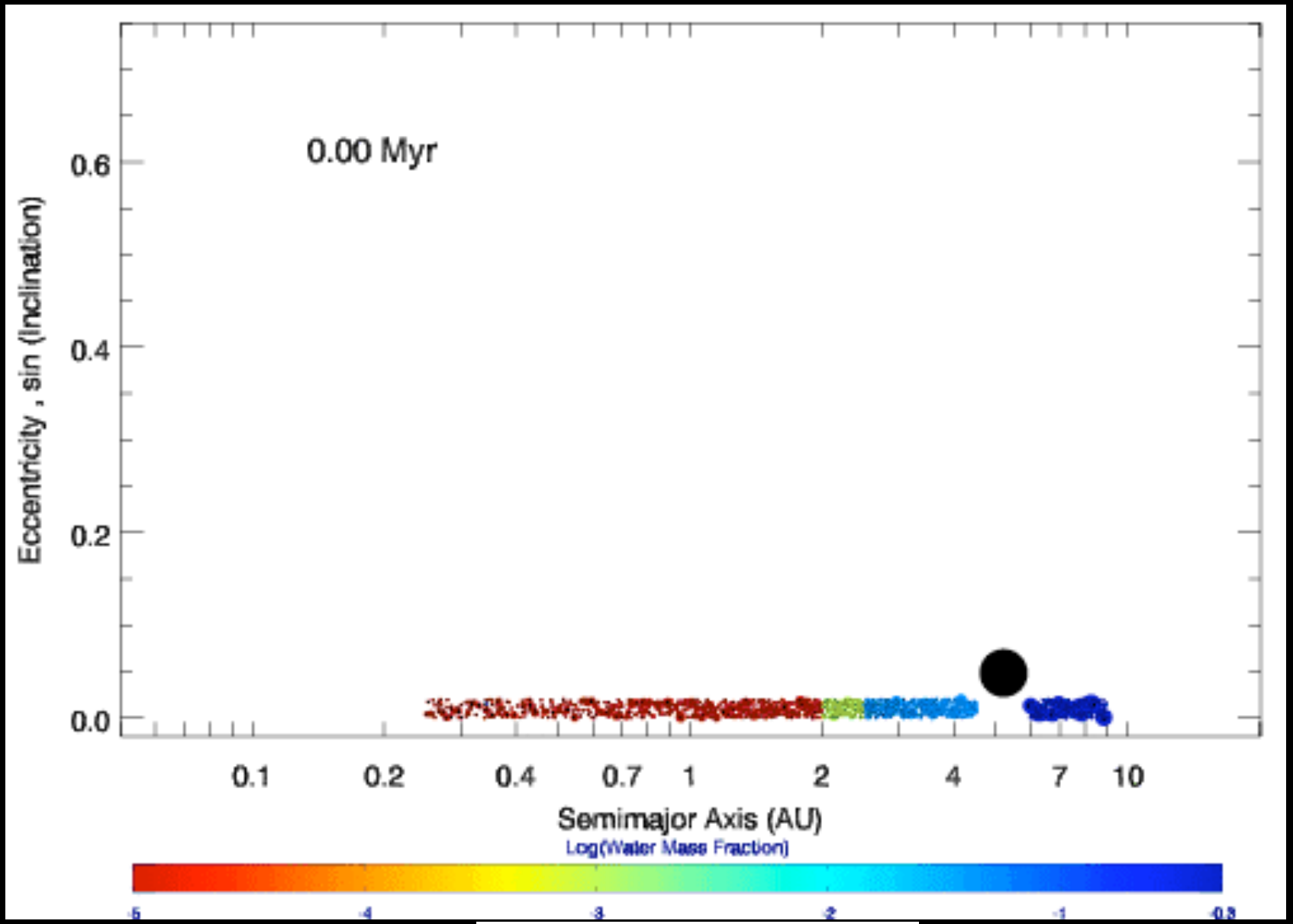




Eccentricity, sin (Inclination)

Log Semimajor Axis

Raymond, Mandell & Sigurdsson 2006



Eccentricity, sin (Inclination)

Log Semimajor Axis

Raymond, Mandell & Sigurdsson 2006


Credit: Nahks Tr'Enhl

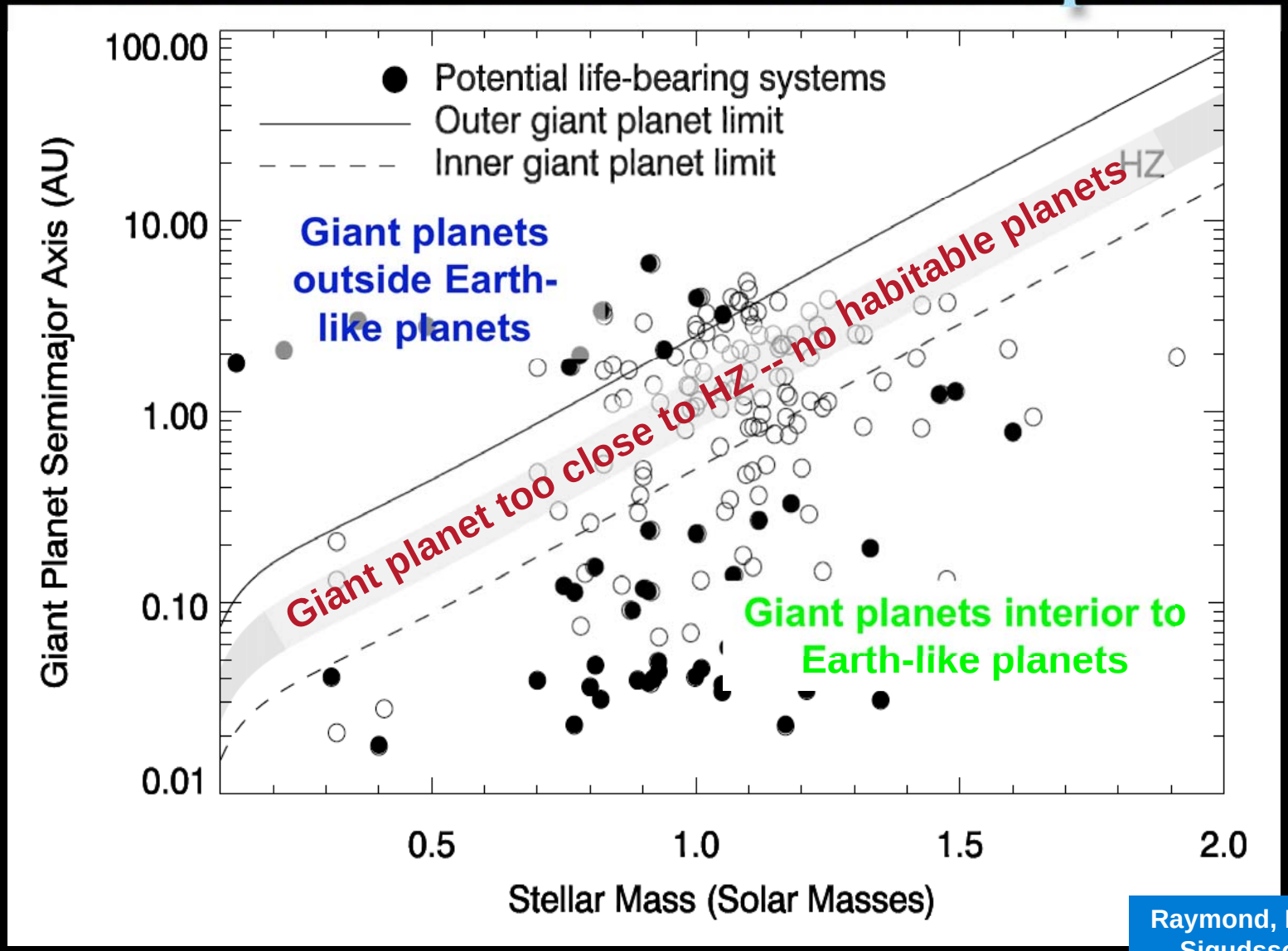

Credit: Nahks Tr'Enhl

Can the giant planets we see tell us something about the Earth-like planets we can't see?

YES.

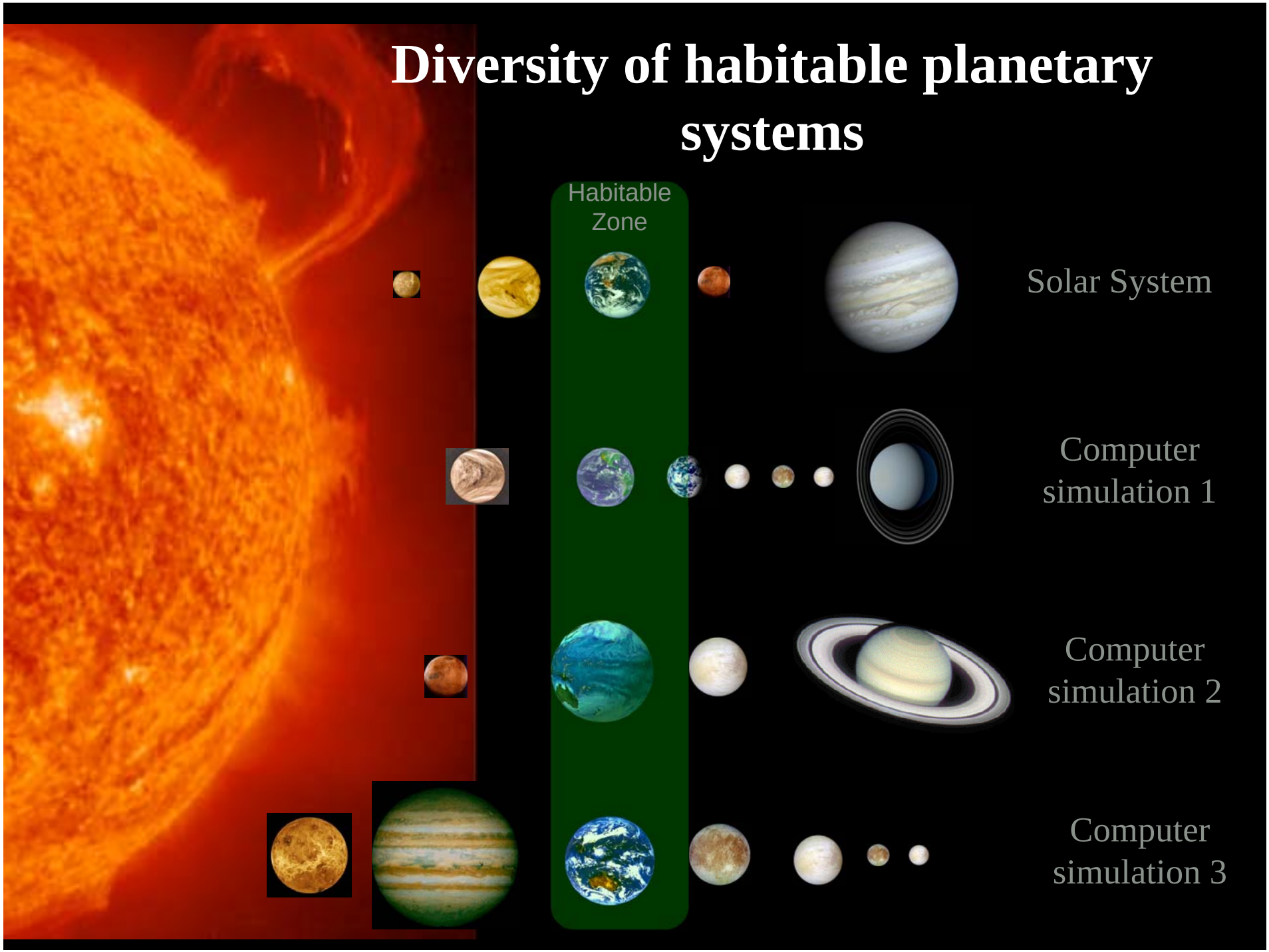
- Giant planets form faster than terrestrial planets
- Final stage of terrestrial planet growth is strongly affected by gravitational influence of giant planets

About 1/3 of known exoplanet systems could have formed a habitable planet

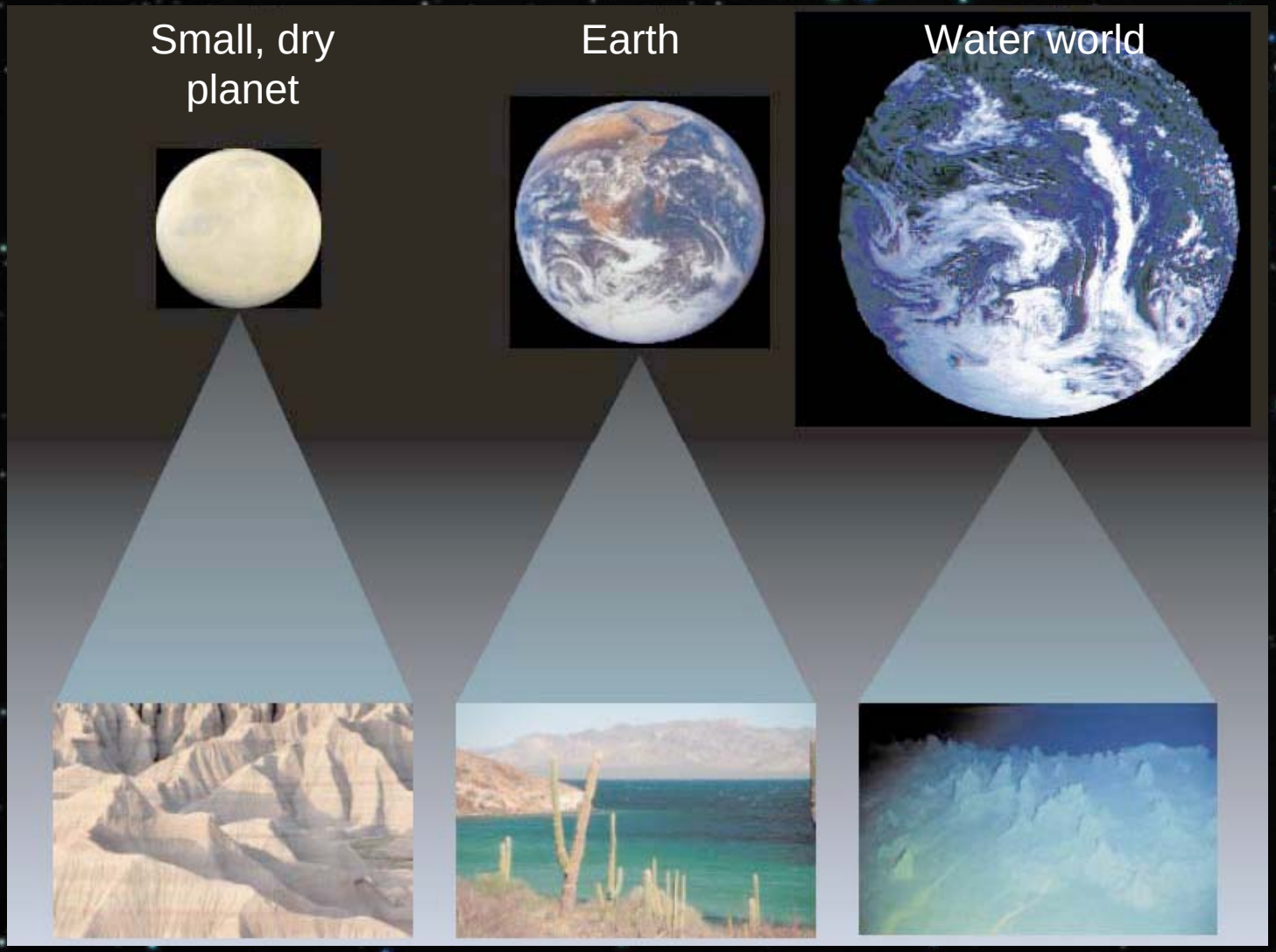


Raymond, Mandell & Sigudsson 2006

Diversity of habitable planetary systems



What might the surfaces of these planets look like?



Lissauer 1999

Conclusions

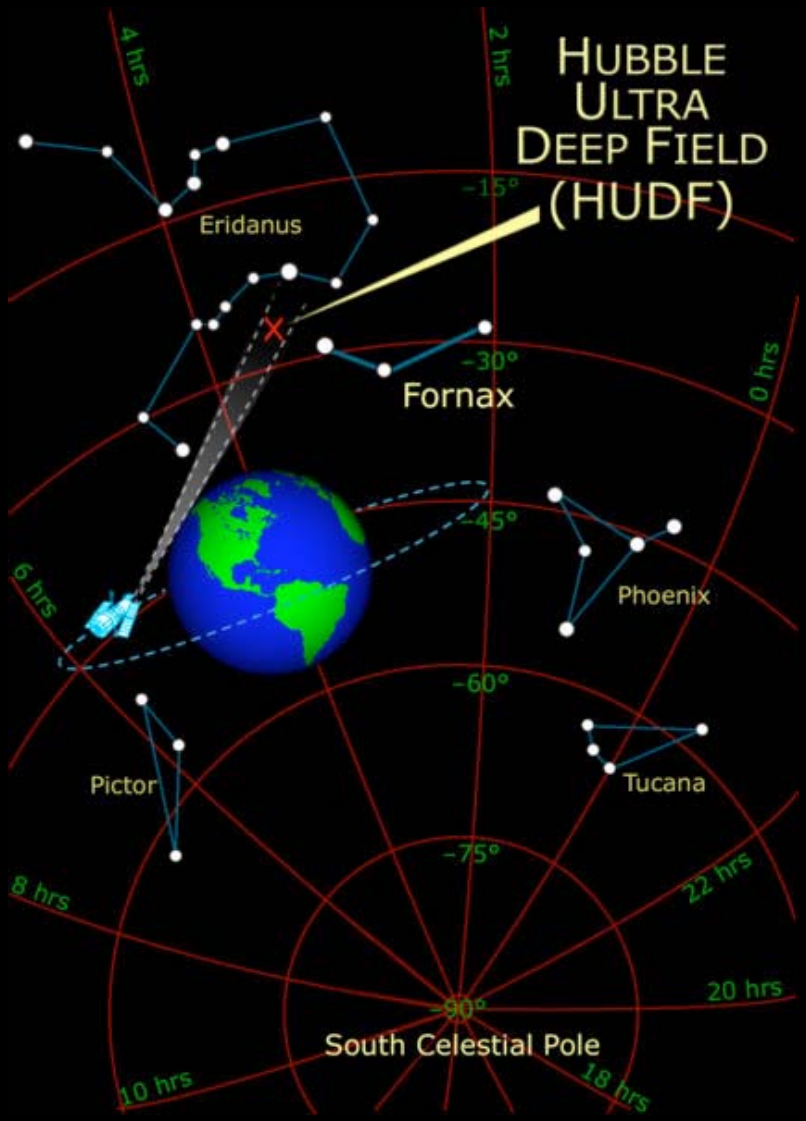
Diversity of terrestrial planets, in terms of mass, orbits, composition

Earth-like planets can form in hot Jupiter systems but should be “water worlds”

Growth of terrestrial planets is affected by giant planets! Can begin to predict the nature & habitability of extrasolar terrestrial planets

→ Useful for upcoming missions (Kepler, Terrestrial Planet Finder)

How many planets are out there?



The Hubble Space Telescope stared at a dark patch of sky for 15 days straight

- 100s of billions stars in our galaxy
- 100s of billions of galaxies in the Universe
- Probably quintillions of planets (1,000,000,000,000,000,000)

Additional Information

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Credit: Nahks Tr'Enhl (nahks.com)

Additional Slides

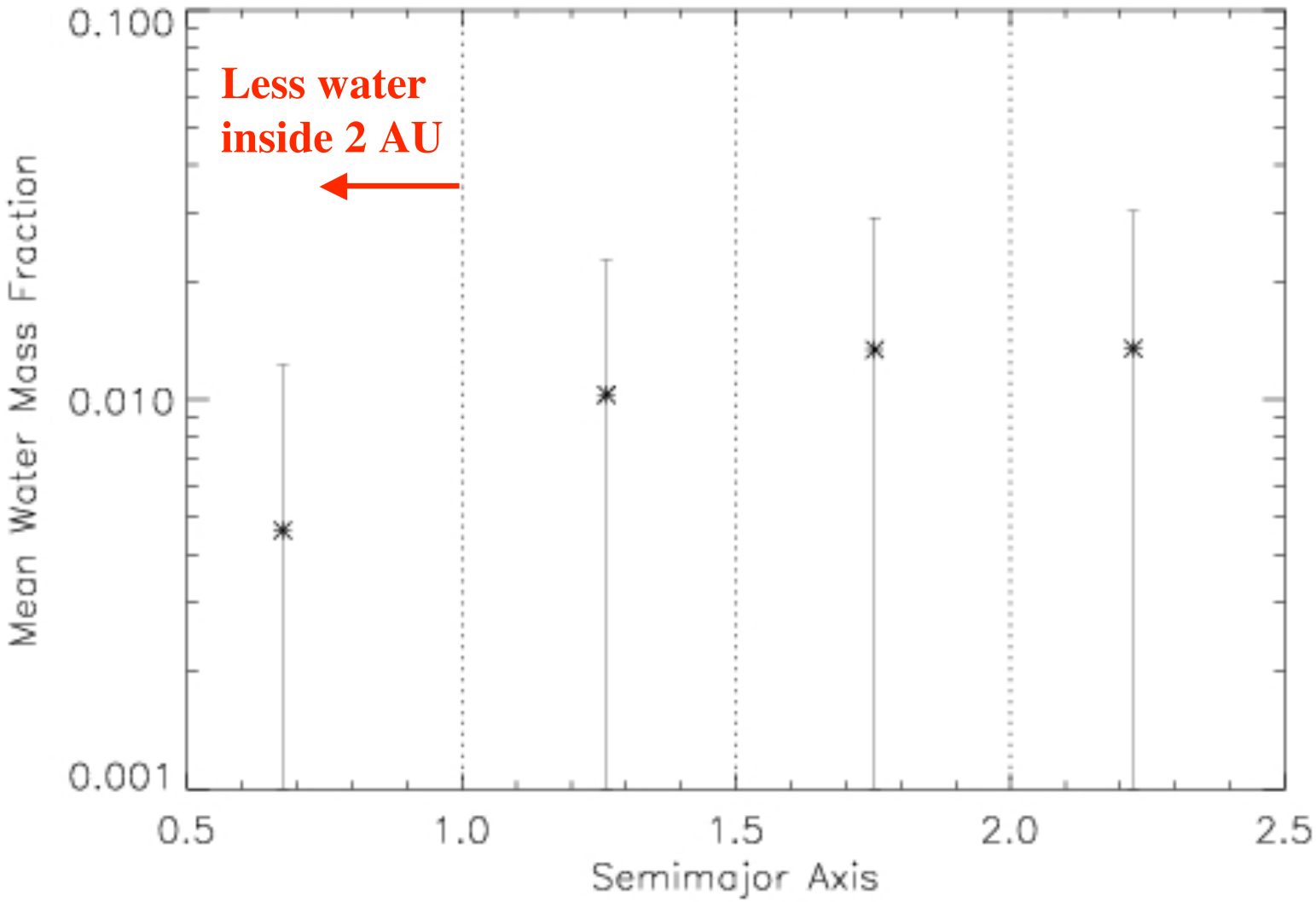
Collaborators

- Tom Quinn (Washington)
- Jonathan Lunine (Arizona)
- Avi Mandell (Penn State)
- Rory Barnes (Arizona)
- John Scalo (Texas)
- Steinn Sigurdsson (Penn St.)
- Vikki Meadows (Caltech)
- John Chambers (CIW)
- Nader Haghighipour (Hawaii)
- Nate Kaib (Washington)
- Dimitri Veras (Colorado)

Funding: Thanks to NASA Astrobiology Institute (thru the Virtual Planetary Laboratory, based at Caltech)

Credit: Nahks Tr'Enhl

Water content vs orbital radius



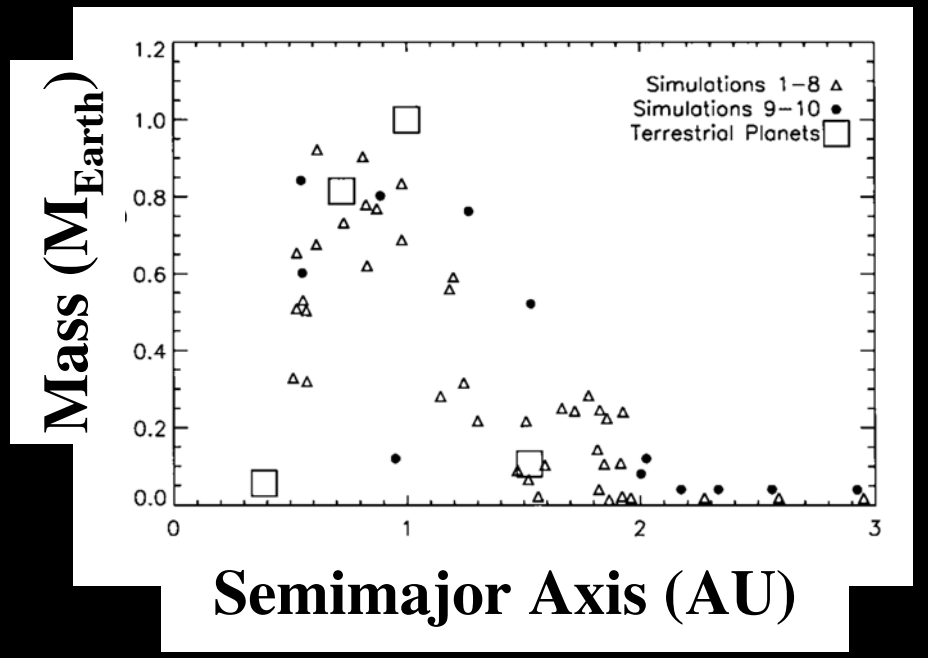
Model for Solar System Formation

Successes

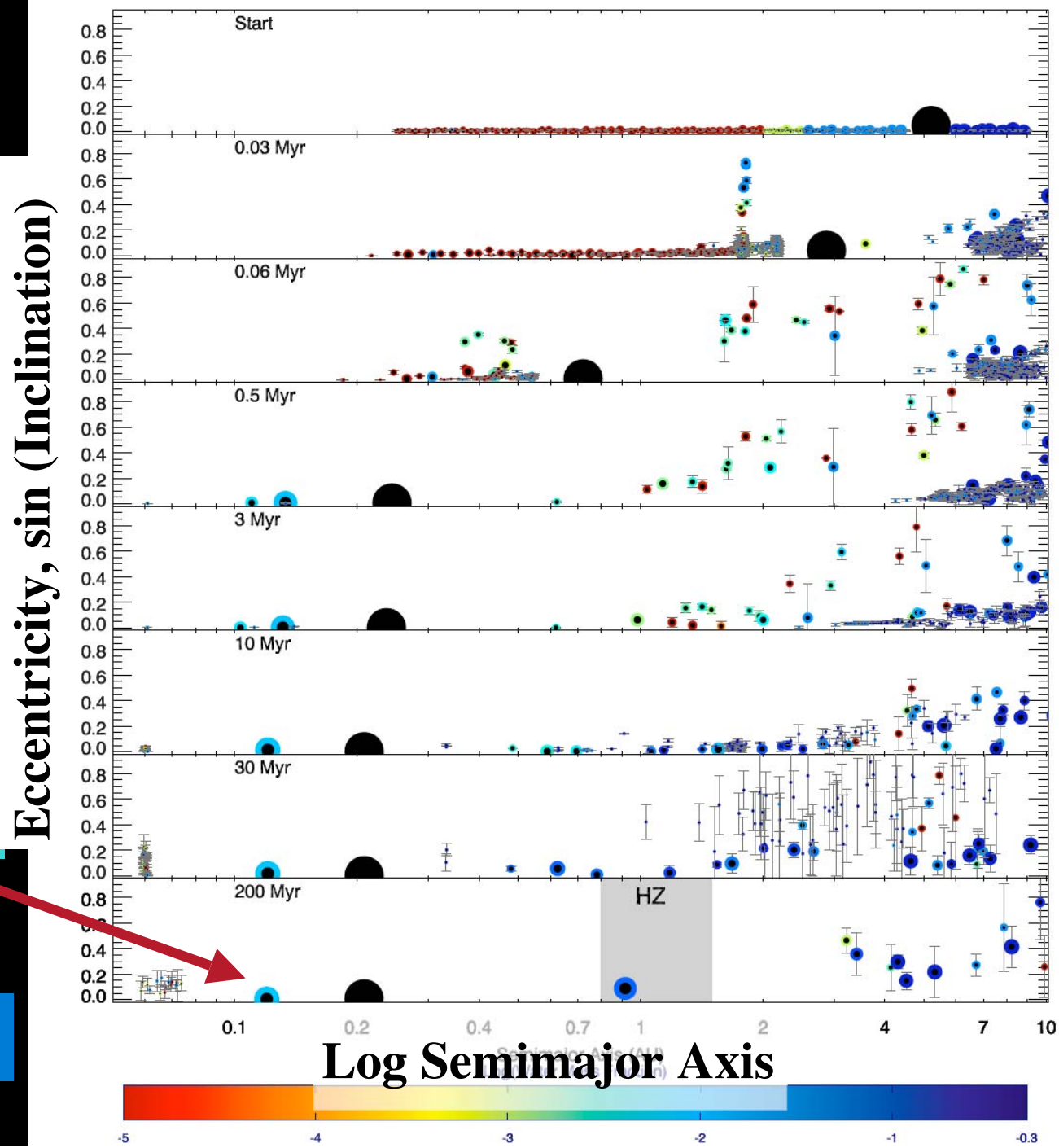
- Can roughly reproduce masses and orbits of terrestrial planets with 20-1000 starting particles (Agnor et al 1999; Chambers 2001; O'Brien et al 2006)
- Asteroidal source explains isotopic ratio of Earth water (Morbidelli et al 2000)

Shortcomings

- Mars is too small (unexplained – Wetherill 1991)
- Mercury is too small and too iron-rich (giant impact? Benz et al 1988, Wetherill 1988)
- Not included: collisional fragmentation (Asphaug et al 2006), water depletion from impacts and hydrodynamic escape (Matsui & Abe 1986, Canup & Pierazzo 2006, Genda & Abe 2005)



Snapshots of a sim with giant planet migration



A "hot Earth"

Raymond, Mandell & Sigurdsson 2006

When are we going to find terrestrial planets around other stars?

- Ground-based radial velocities can find 3-5 M_{Earth} planets in HZ of K stars (Marcy group)
- COROT (ESA): 2006-7
  - can detect 2-3 M_{Earth} planets in HZ
- Kepler (NASA): 2008
  - can detect Earth at 1 AU
  - will survey 100,000 stars, expect ~50 terr. planets
- SIM (NASA): 2011 (delayed…)
  - 1 micro-arcsec astrometric precision in deep mode
  - Hopes to find ~20 Earths
- Terrestrial Planet Finder, Darwin: 10-15 yrs (we hope)
  - spectra of terrestrial planets?
- Web Cash's occulter/starshade (timeline uncertain)