Habitable terrestrial planets: how they form, where they form, and where to look for them

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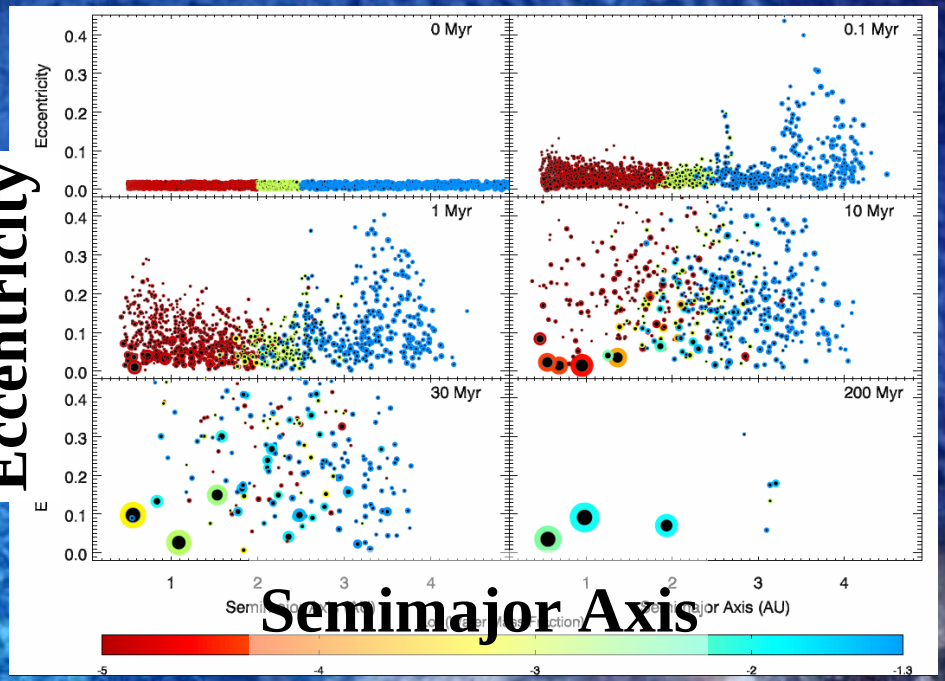
Images stolen shamelessly from NASA

1. How terrestrial planets form

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

(Giant planets form in <10^{6-7} yrs, so affect stages 3 and 4)

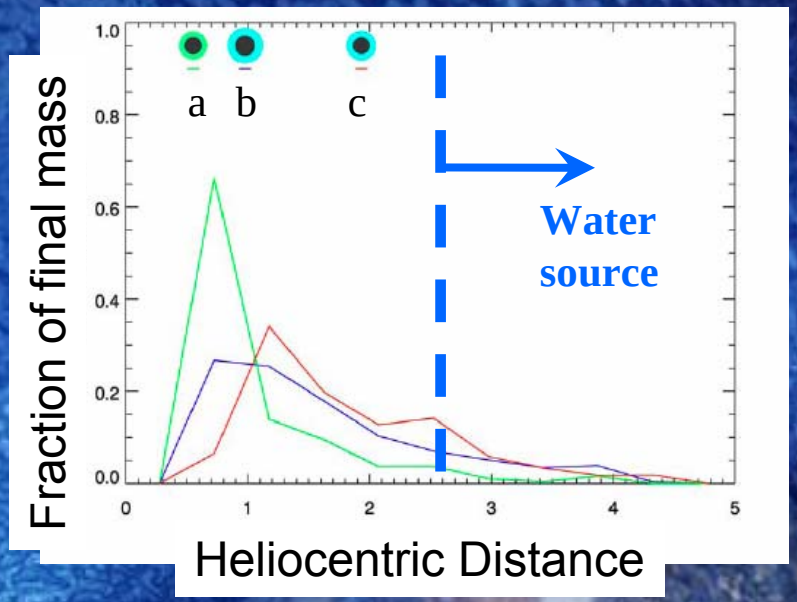


Snapshots in time of a high-res simulation: 1885 initial particles, Jup at 5.5 AU (e_J=0) from Raymond, Quinn & Lunine 2006a

Reviews: Lissauer 1993, Chambers 2004

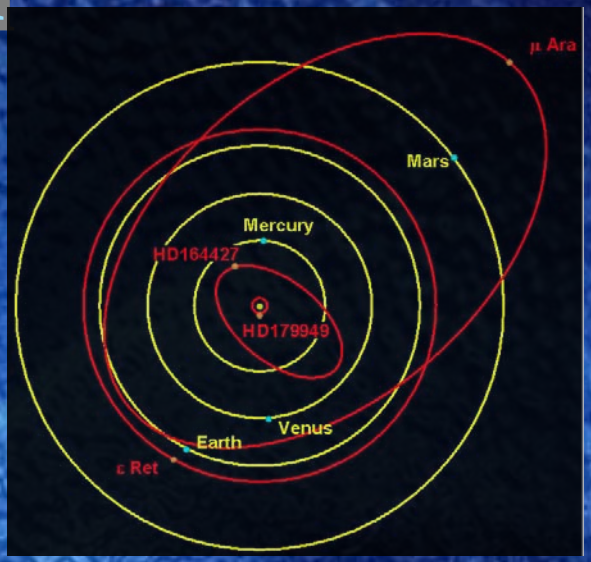
Water Delivery to Earth-like planets

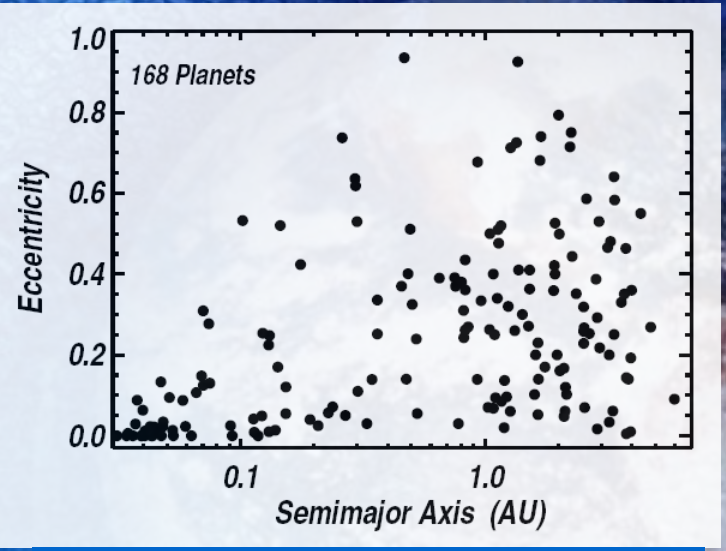
- Sources
  - **Asteroidal (2.5-4 AU)**
  - Cometary (>5 AU)
  - Nebular (1 AU; gas)
- Constraints
  - D/H of Earth's water
  - Mantle composition (Drake & Righter 2002)
  - Dynamics, impact rates
- Robustness (asteroidal)
  - Delivery from few embryos, billions of planetesimals
  - Much less stochastic than previously thought (old: Morbidelli et al 2000, new: Raymond, Quinn, Lunine 2006b)
- **Giant planets are disruptive for terrestrial planet formation, water delivery.**



Key parameters for terrestrial planet formation

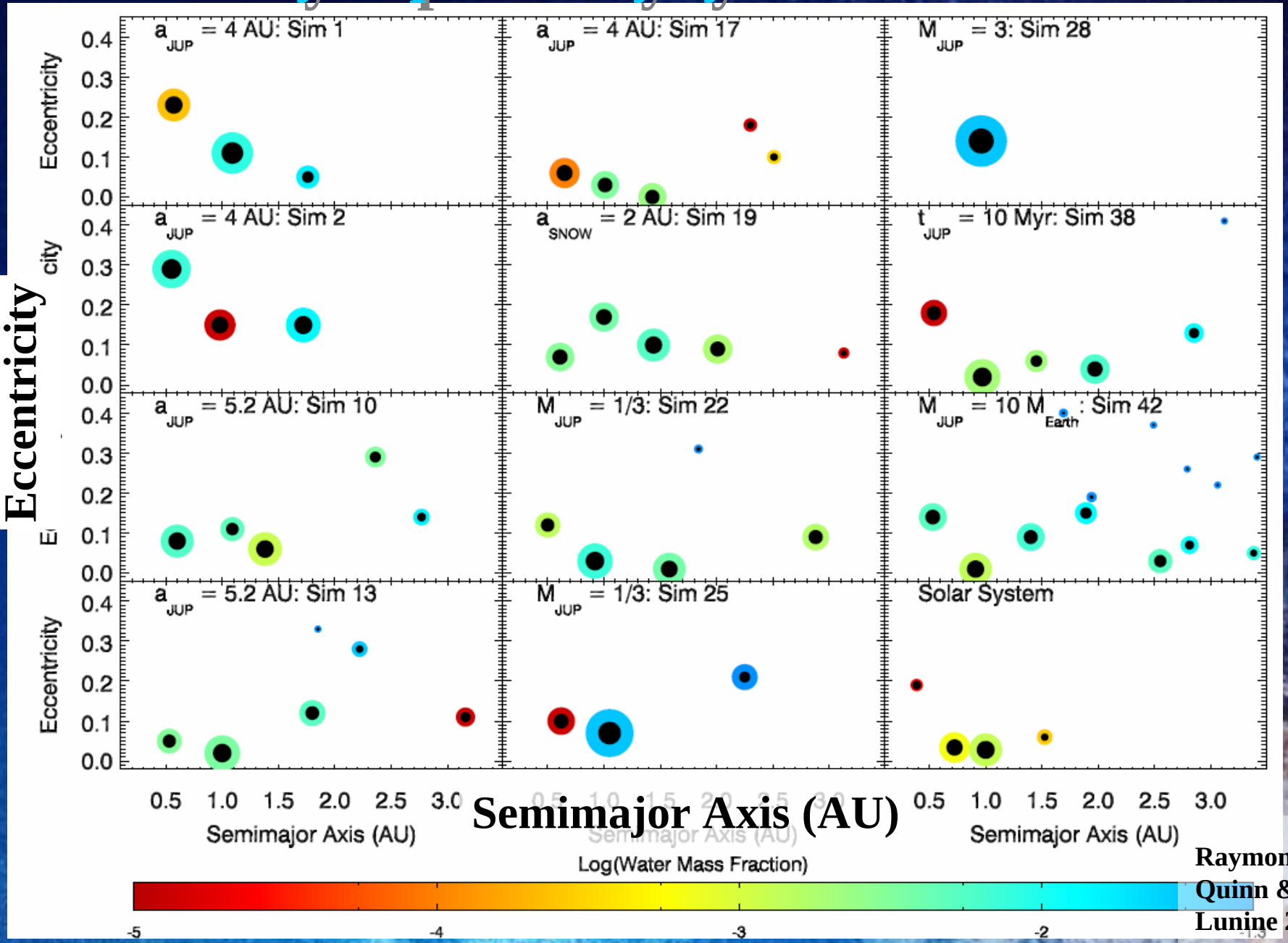
- Protoplanetary disk mass
  - Range of 1-2 orders of magnitude for given stellar mass
  - Disk mass scales with stellar mass (~linearly)
- Disk surface density profile
  - Affects planet mass, formation time, composition
  - New models suggest slope of 0.5-1, not 1.5 (MMSN)
- **Giant planets**
  - **Mass**
  - **Orbital distance**
  - **Orbital eccentricity**





Butler et al 2006; www.exoplanets.org

Diversity in planetary systems like our own



Raymond, Quinn & Lunine 2004

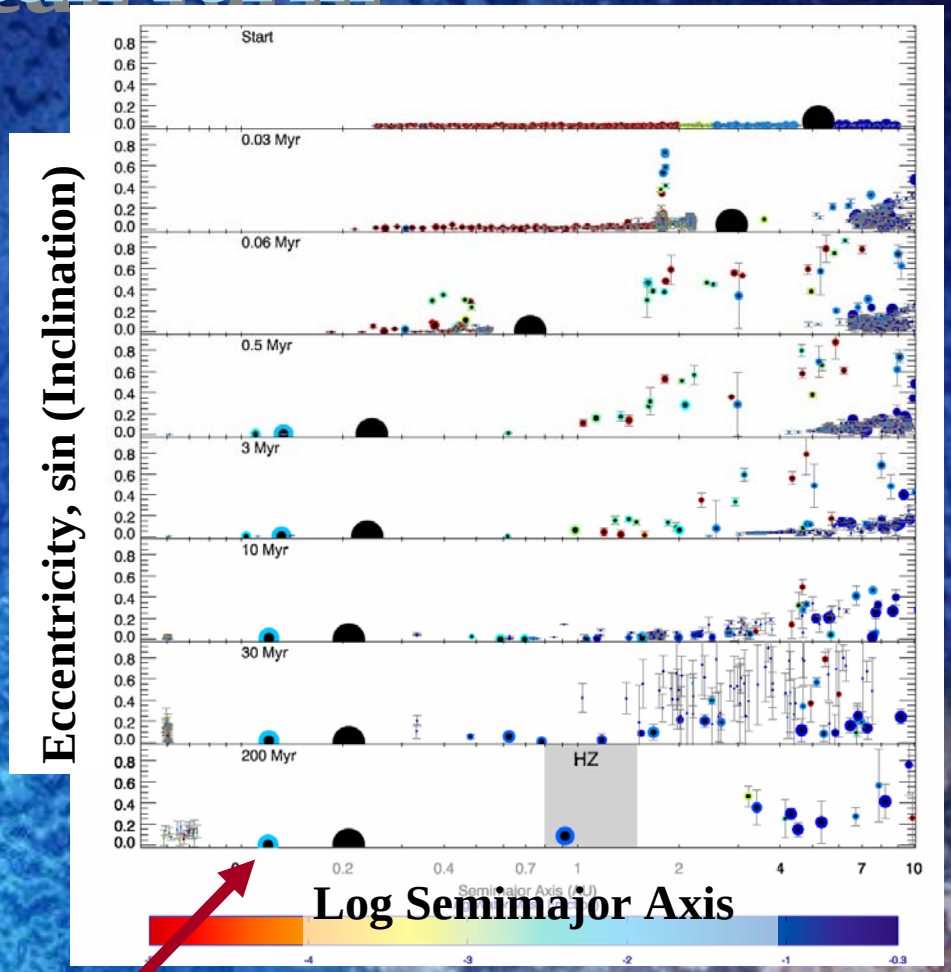
2. Where habitable terrestrial planets can form

Where they form

- In systems with outer giant planets
- In “hot Jupiter” systems
  - Ocean planets
- In systems with no giant planets
  - Inferred from debris disk observations (Greaves et al 2006)

Where they don’t form

- Systems with large giant planet eccentricities
- In systems with giant planets in HZ
  - Habitable moons? (Williams et al 1997)

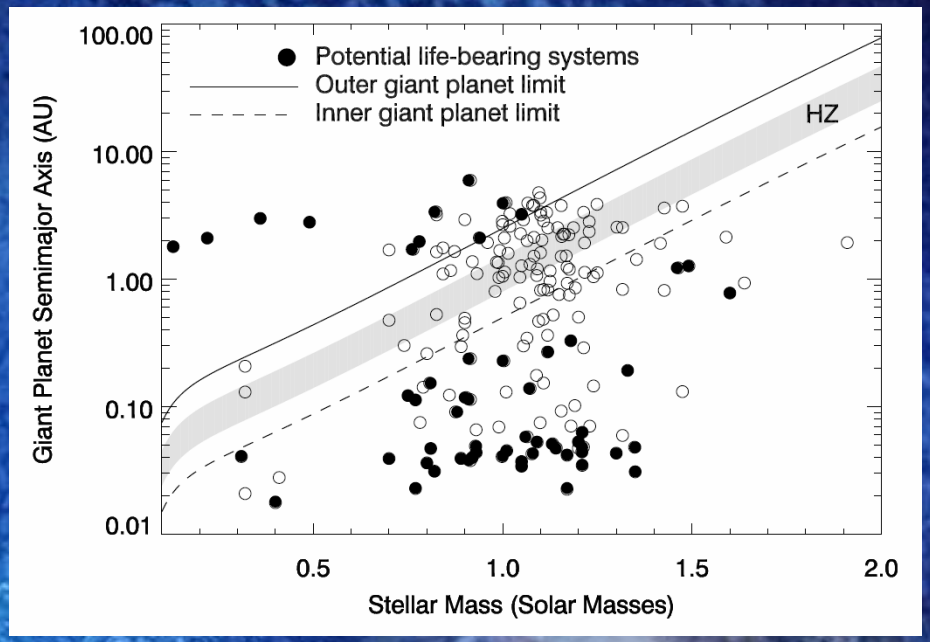


A “hot Earth”

Raymond, Mandell & Sigurdsson 2006

3. Where to look for habitable planets

- For Sun-like star, need giant planet inside 0.5 AU or outside 2.5 AU
- Need relatively low-ecc. giant planet orbits (Raymond 2006)
- Other important factors
  - Disk mass
    - Range for given stellar mass (e.g., Eisner & Carpenter 2003)
    - Scaling with stellar mass (Scholz et al 2006; Raymond, Scalo & Meadows 2006): K stars might be good targets
  - Stellar metallicity
  - Giant planet mass
- Note: more robust than stability studies (Menou, Jones)
  - Asteroid belt has no Earth



About 1/3 of known systems could host a habitable planet

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): 2009
  - can detect Earth at 1 AU
  - Expects 100s of terr. planets, ~50η_{Earth} hab. 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)

Additional Information

- raymond@lasp.colorado.edu
- Poster in TPF session
- Talk to me!

Credit: Nahks Tr'Enhl

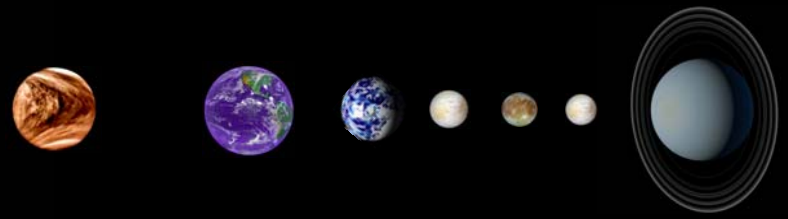
Additional Slides

Differences in Planetary Systems come from Two Sources

1. Stochastic variation in the accretion process
   (e.g. Wetherill 1996; Chambers 2001)
2. Systematic variations among systems
   - Number, masses, orbits of giant planets (Chambers & Cassen 2002; Levison & Agnor 2003; Raymond, Quinn & Lunine 2004; Raymond 2006)
     - 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 (Chambers & Cassen 2002; Raymond, Quinn & Lunine 2004, 2005, 2006)
     - Higher surface density $\Rightarrow$ fewer, more massive terrestrial planets
     - Higher α (steeper profile) $\rightarrow$ 1) Planets closer to star, 2) More massive planets, 3) Faster planet growth, 4) Lower water content, 5) Higher iron content

Diversity of habitable planetary systems

Solar System

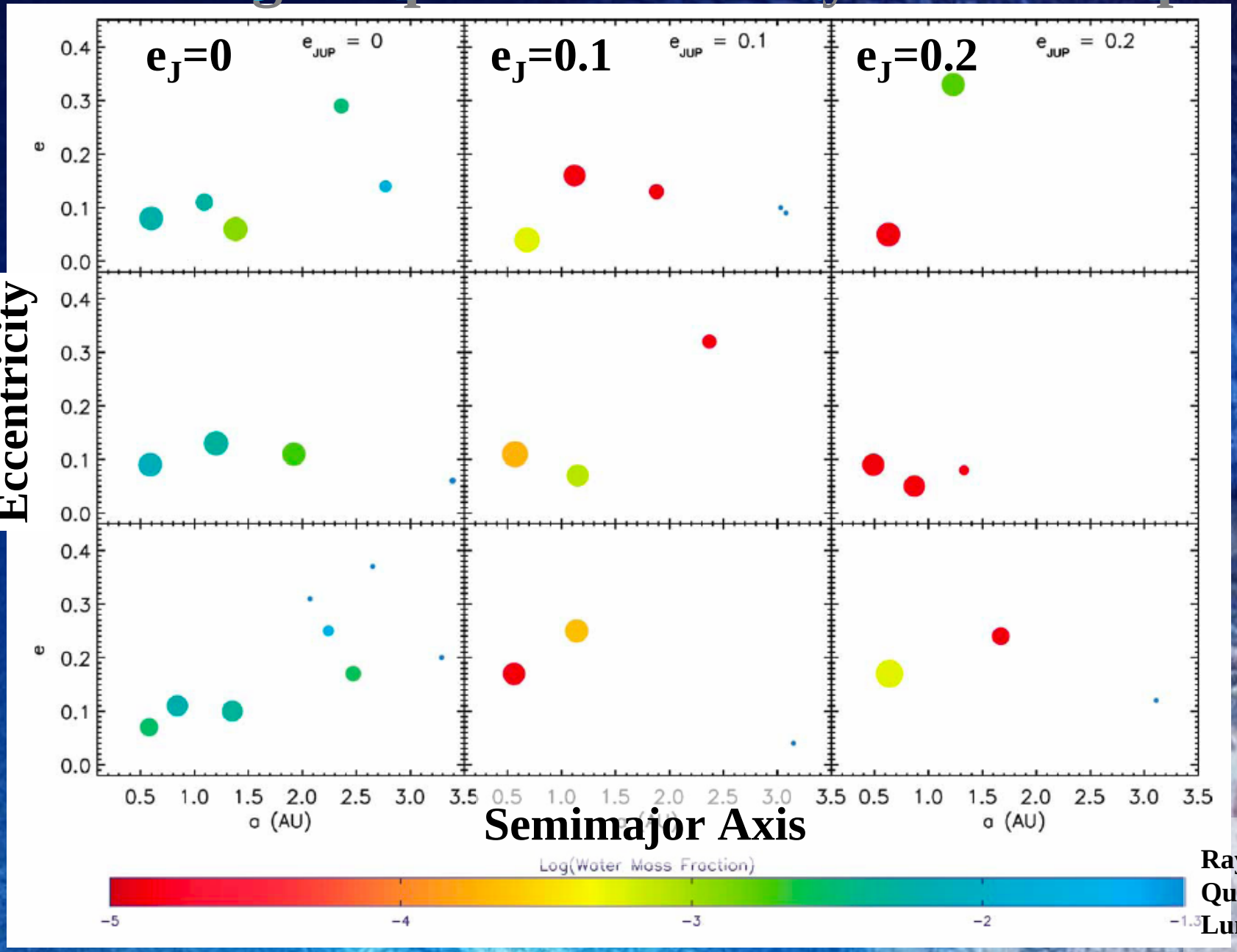


Giant Planet is 10 M_{Earth}

"Water world" in HZ

"Water world" in hot Jupiter system

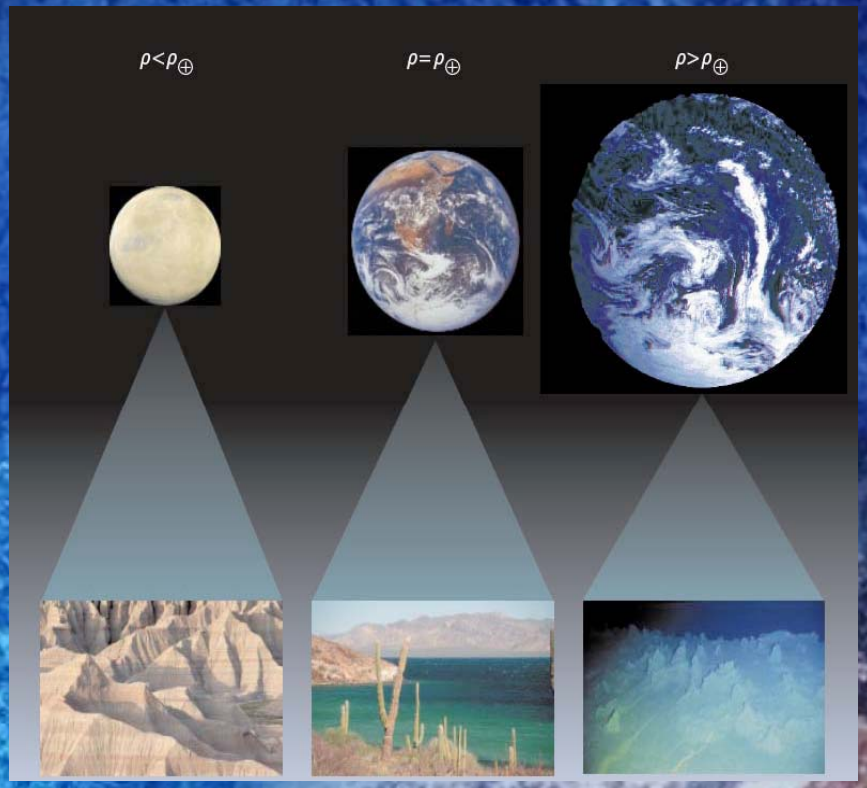
Eccentric giant planets form dry terrestrial planets



Raymond, Quinn & Lunine 2004

Physical requirements for "sustainably habitable" planets

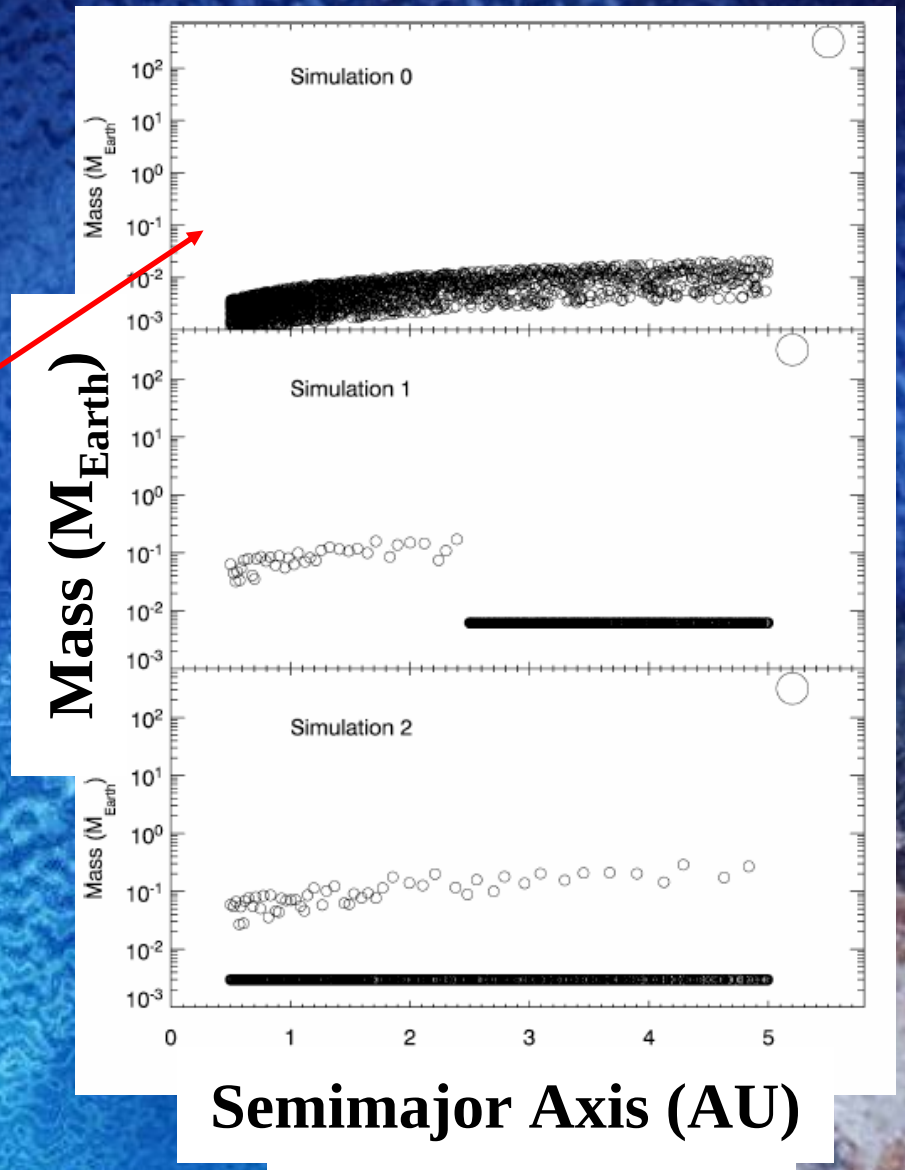
- Thick atmosphere? (>0.12 Earth masses for N according to Williams et al 1997)
- Plate tectonics? (for CO_2/carbonate cycle; >0.23 earth masses Williams et al 1997)
- Following Williams et al, if density ~ 4.5 g/cm^3 and lifetime of tectonic activity is 5 Gyr, then limiting mass is about **0.3 Earth masses**



Lissauer 1999

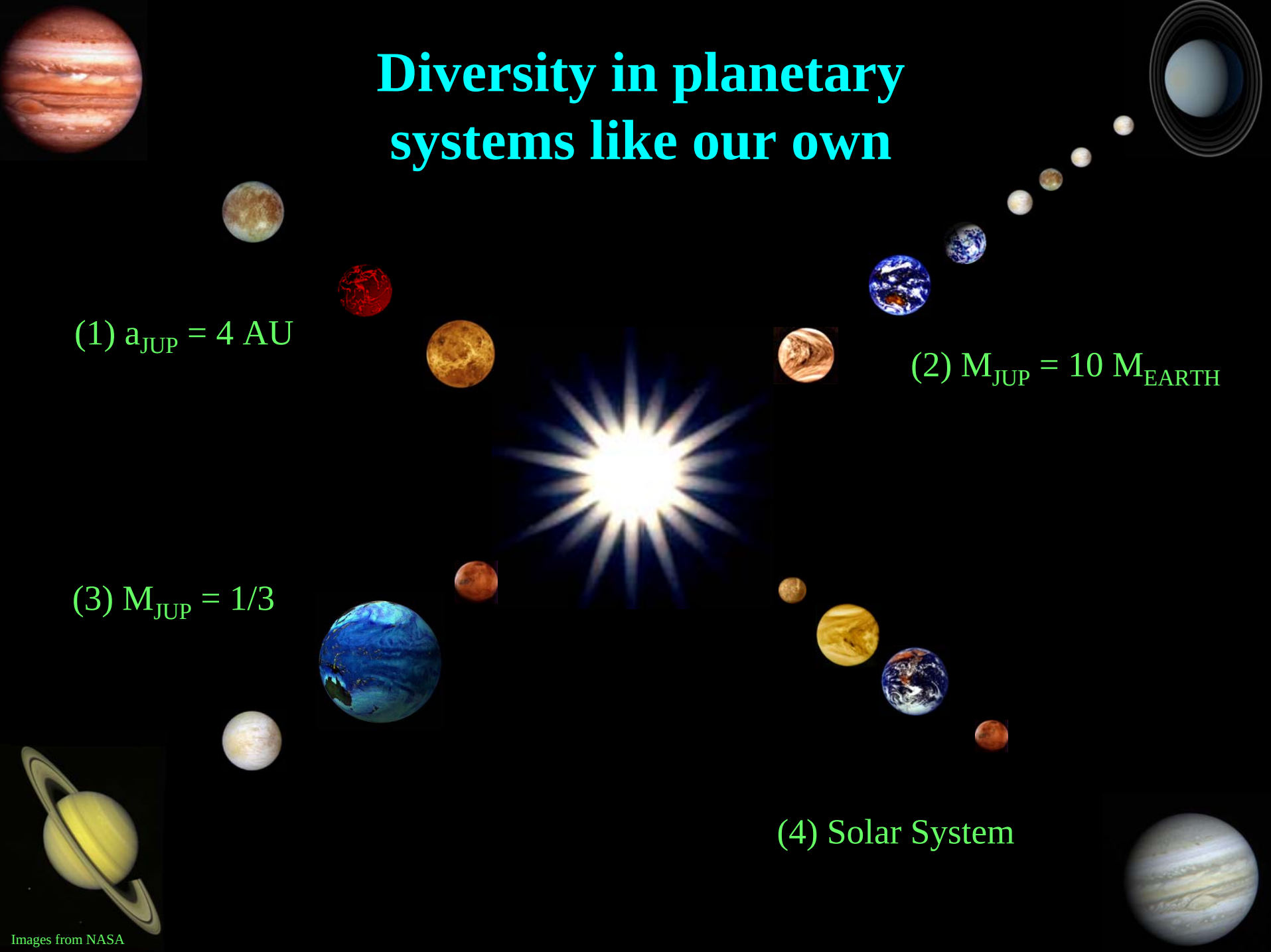
Initial conditions

- Final assembly starts at end of "oligarchic growth" phase: equal mass in:
  - 50-fewx100 embryos
  - Trillions of km-sized planetesimals
- Sim 0: starts in late stages of olig. growth
  - 1885 initial particles between 0.5-5 AU
  - $0.0008 < M < 0.01\ M_E$
  - Total mass 9.9 M_{Earth}
  - Jup. at 5.5 AU, e=0



Raymond, Quinn & Lunine 2006

Diversity in planetary systems like our own



Images from NASA

Habitable planets around low-mass stars?

- Disk mass ~ M_*^h, where h~1 (uncertain; Scholz et al 2006)
- Range of disk masses for a given stellar mass (e.g., Eisner & Carpenter 2003)
- Luminosity steep function of M_*, so HZ very close-in for low-mass stars.
- Mass available to form habitable planets decreases quickly around low-mass stars (depends on h)

Planets >0.3 M_{Earth} in HZ may be rare around low-mass stars! (Raymond, Scalo & Meadows 2006)

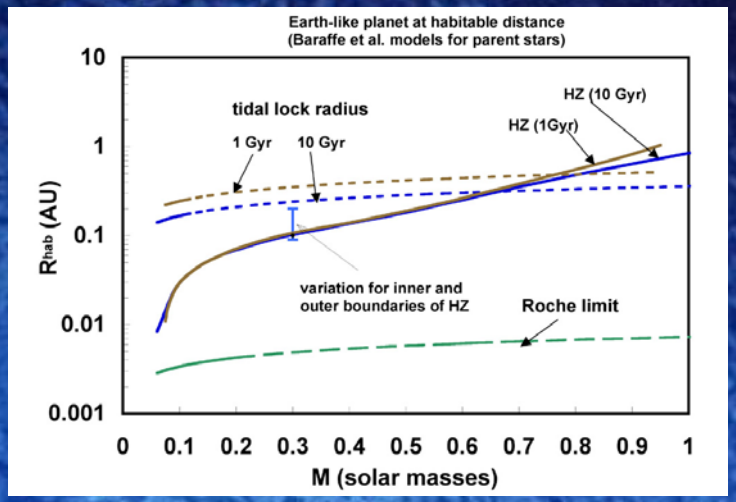
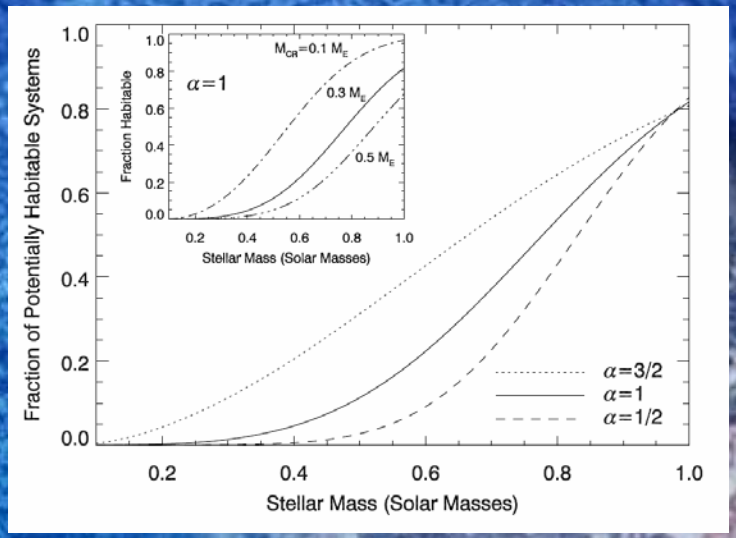


Figure courtesy John Scalo



Raymond, Scalo & Meadows 2006

Disk mass and scaling is key!

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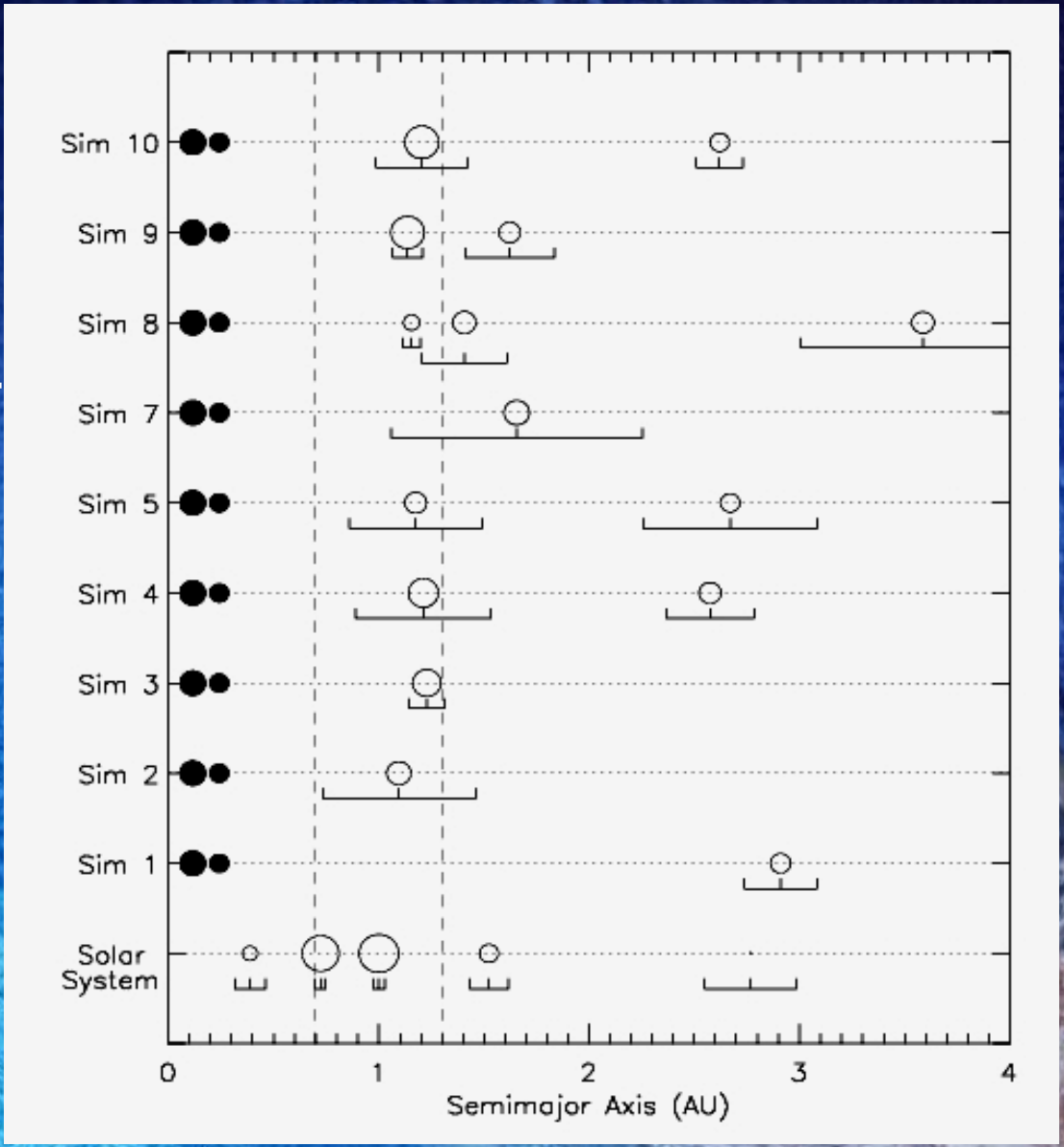
- System with 3 planets at 0.12, 0.24 and 5.9 AU
- terrestrial planets can form, up to 0.6 earth masses, some with water