Water delivery and terrestrial planet formation

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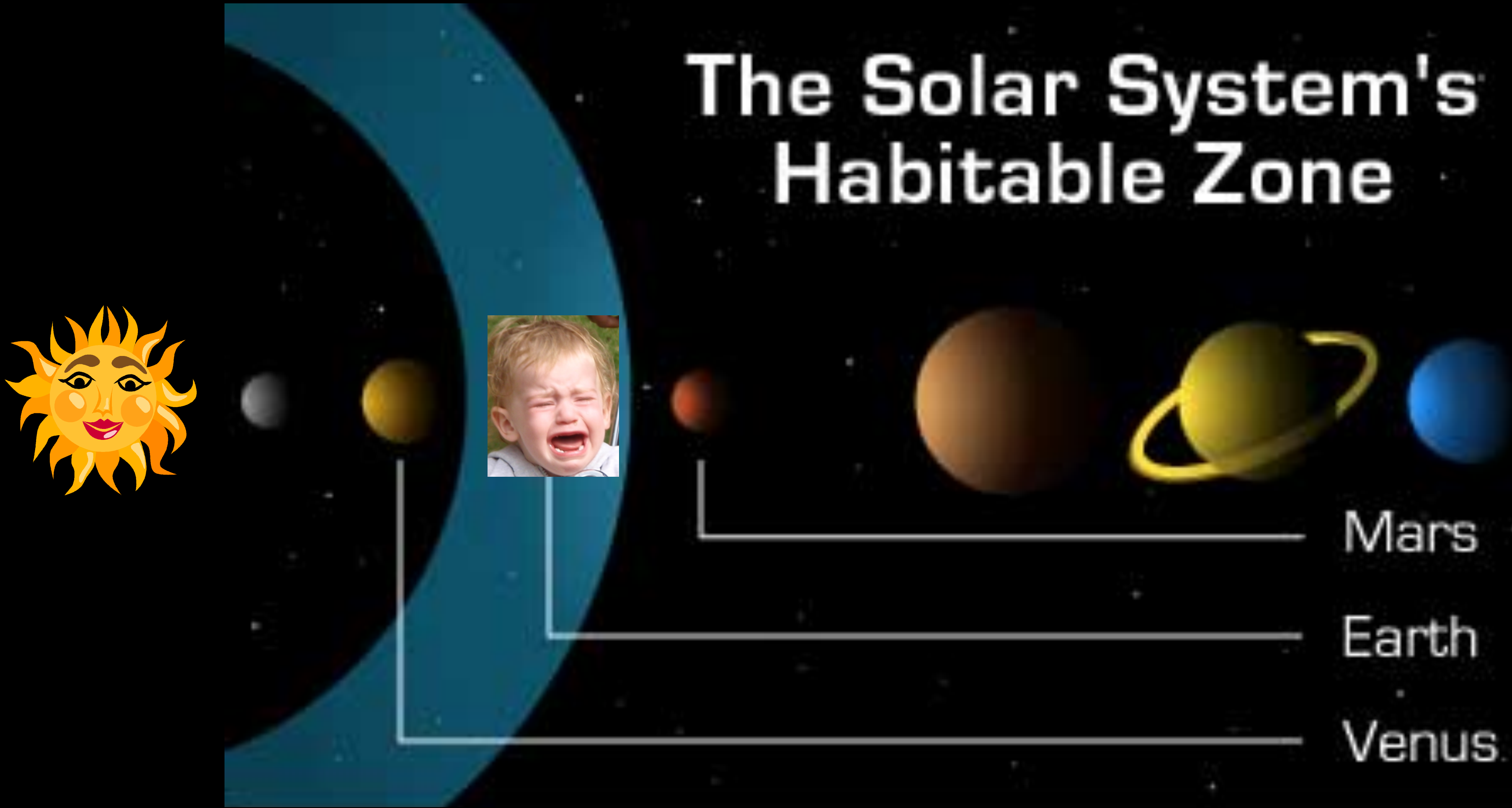
Credit: Nahks Tr'Enhl

Who cares about water?



Dry planets suck!

Who cares about water?

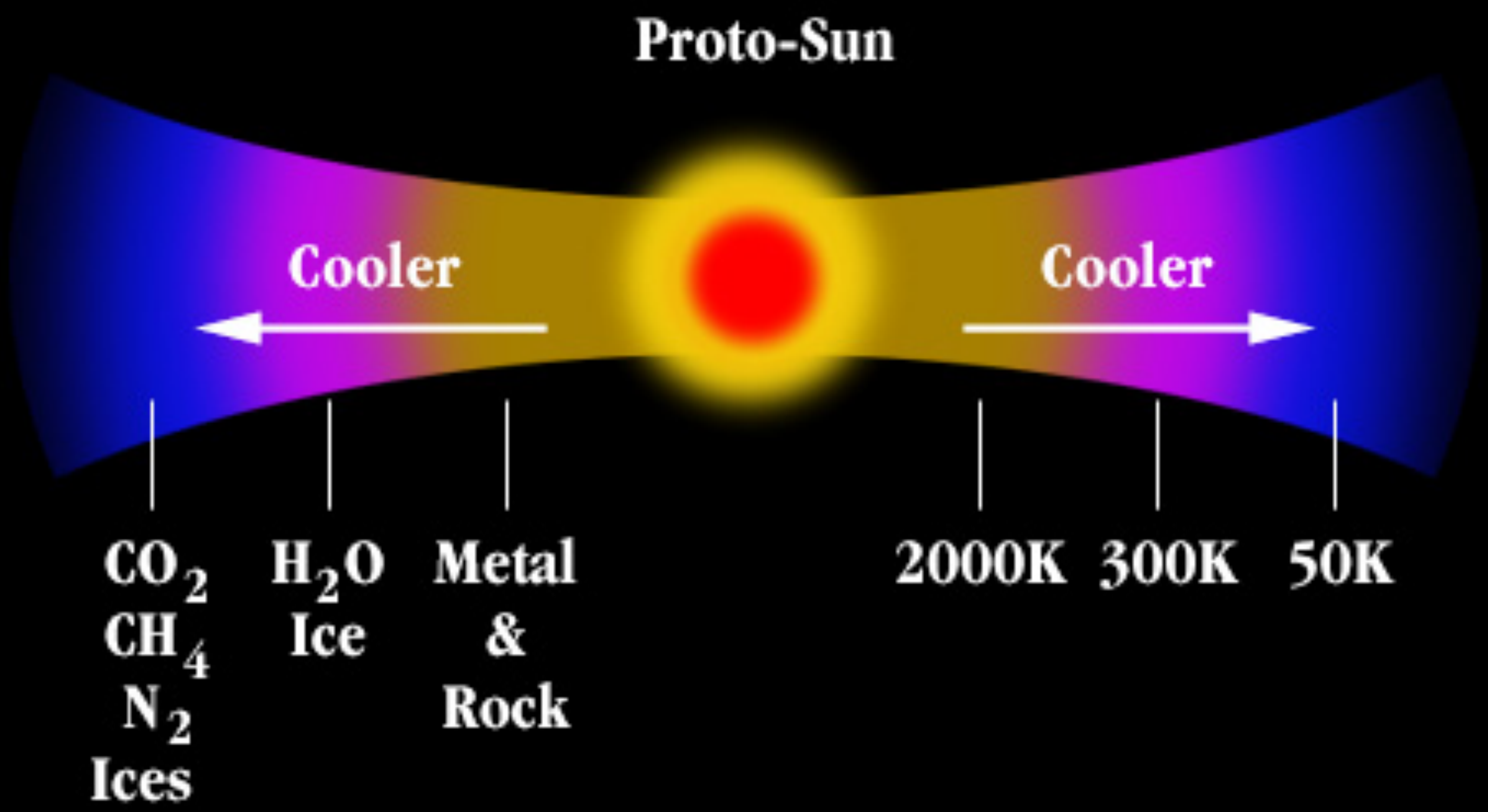
Universal symbol for life

Outline

- Origin of Earth's water
- Terrestrial planet formation and water delivery in extra-solar planetary systems
  - Giant planet migration
  - Unstable giant planets

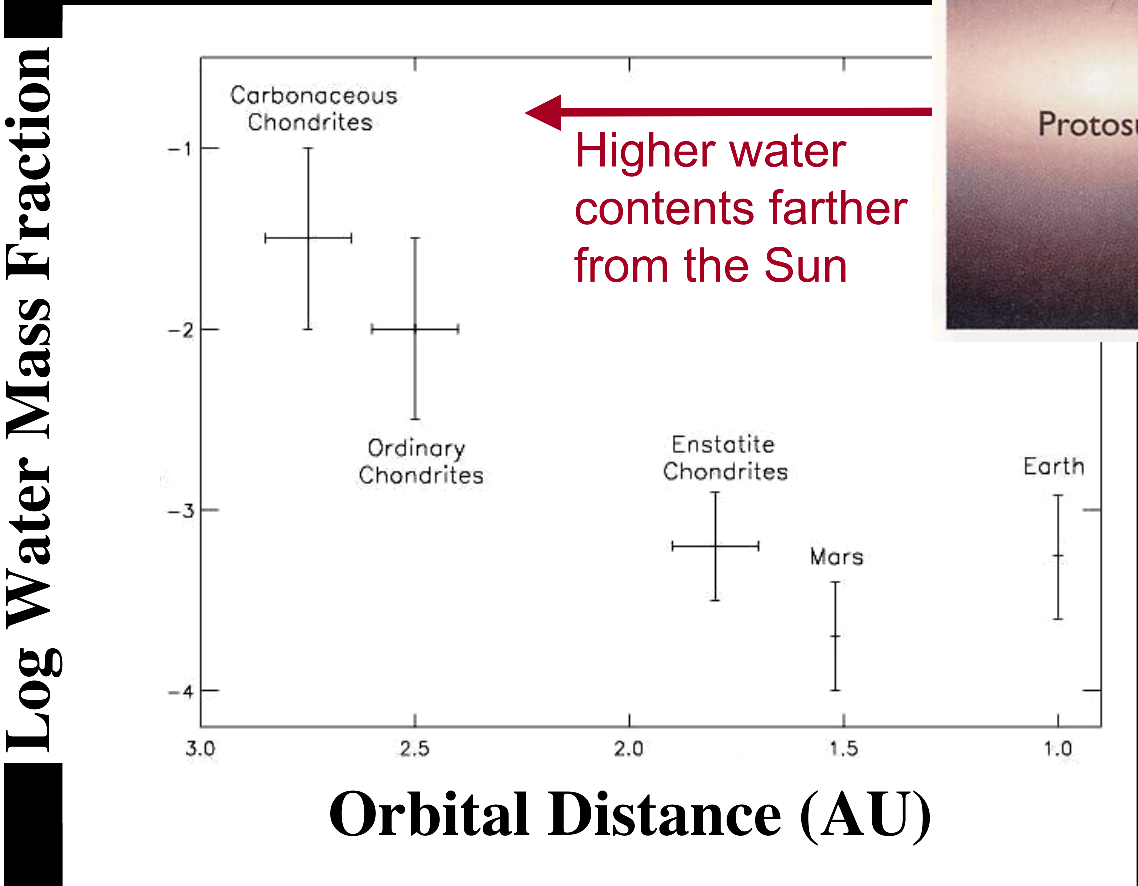

Origin of Earth’s water

The Solar Nebula

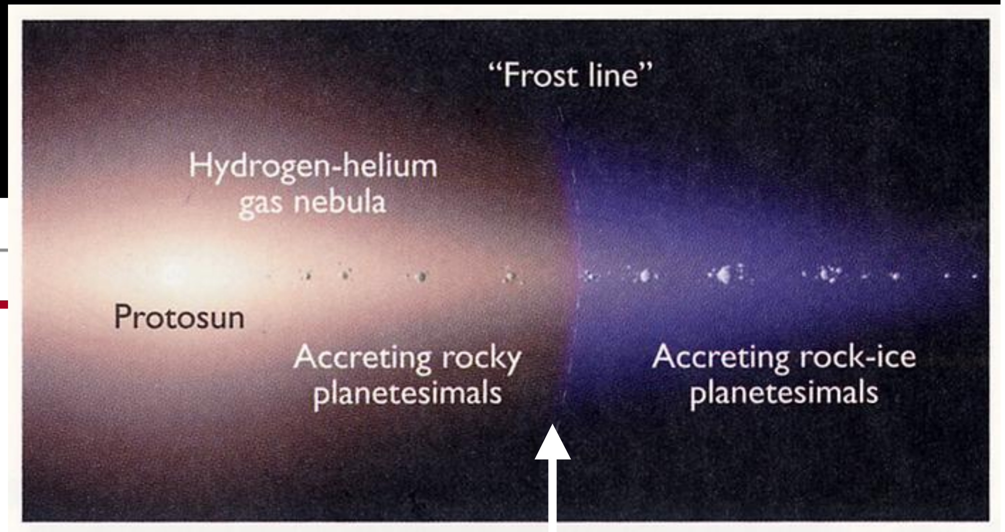


Available solids determined by disk temperature distribution and condensation temperatures

The Solar Nebula



Higher water contents farther from the Sun



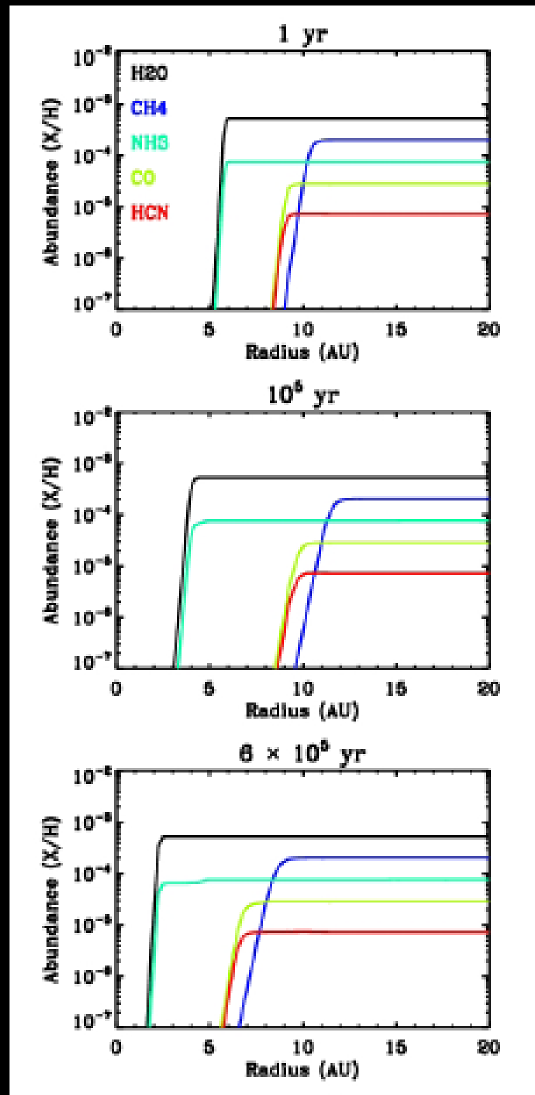
T ~ 170 K

Disk temperature profile imprinted on primitive bodies; Lifetime of gaseous disk is few Myr

Where was the snow line in the Solar Nebula?

- 5 AU to explain Jupiter?
- 2.7 AU to explain S vs C type asteroids?
- ~1 AU to follow models?
  (Sasselov & Lecar 2000; Lecar et al 2006; Ciesla & Cuzzi 2006; Kennedy & Kenyon 2008; Podolak 2009, …)

Probably beyond Mars, but moving inward in time as disk cooled

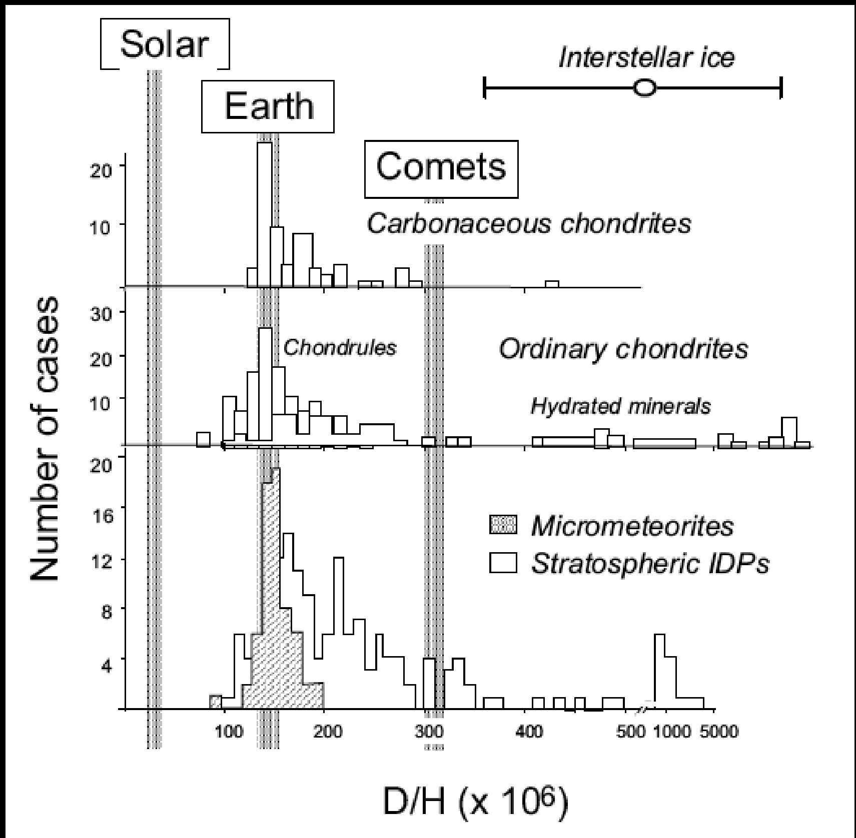


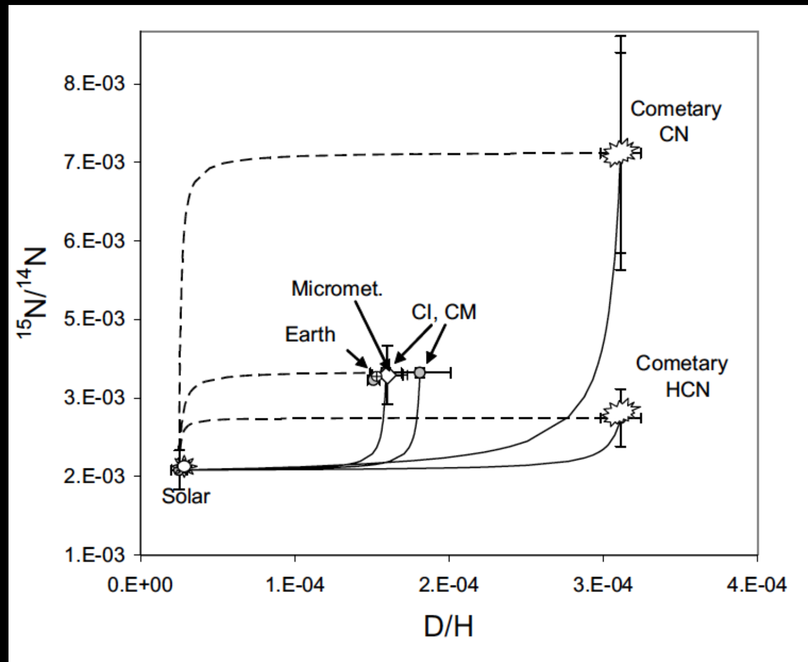
Dodson-Robinson et al 2009

Potential sources of Earth's water

1. Local
   - adsorption onto grains (Drake et al; Muralidharan et al 2008)
   - oxidation of H envelope (Ikoma & Genda 2007)
2. Primitive asteroids (Morbidelli, Chambers, Lunine et al 2000; Chambers & Cassen 2002; Raymond et al 2007)
3. Comets (Delsemme 1992; Owen & Bar-Nun 1995)

Asteroidal source is currently most plausible
(with plenty of uncertainties)

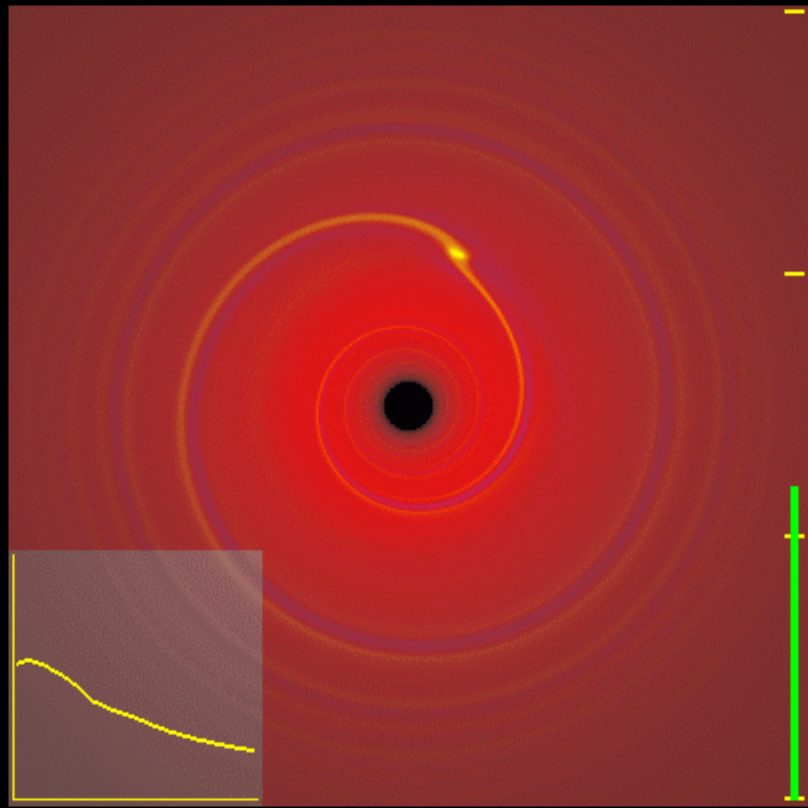




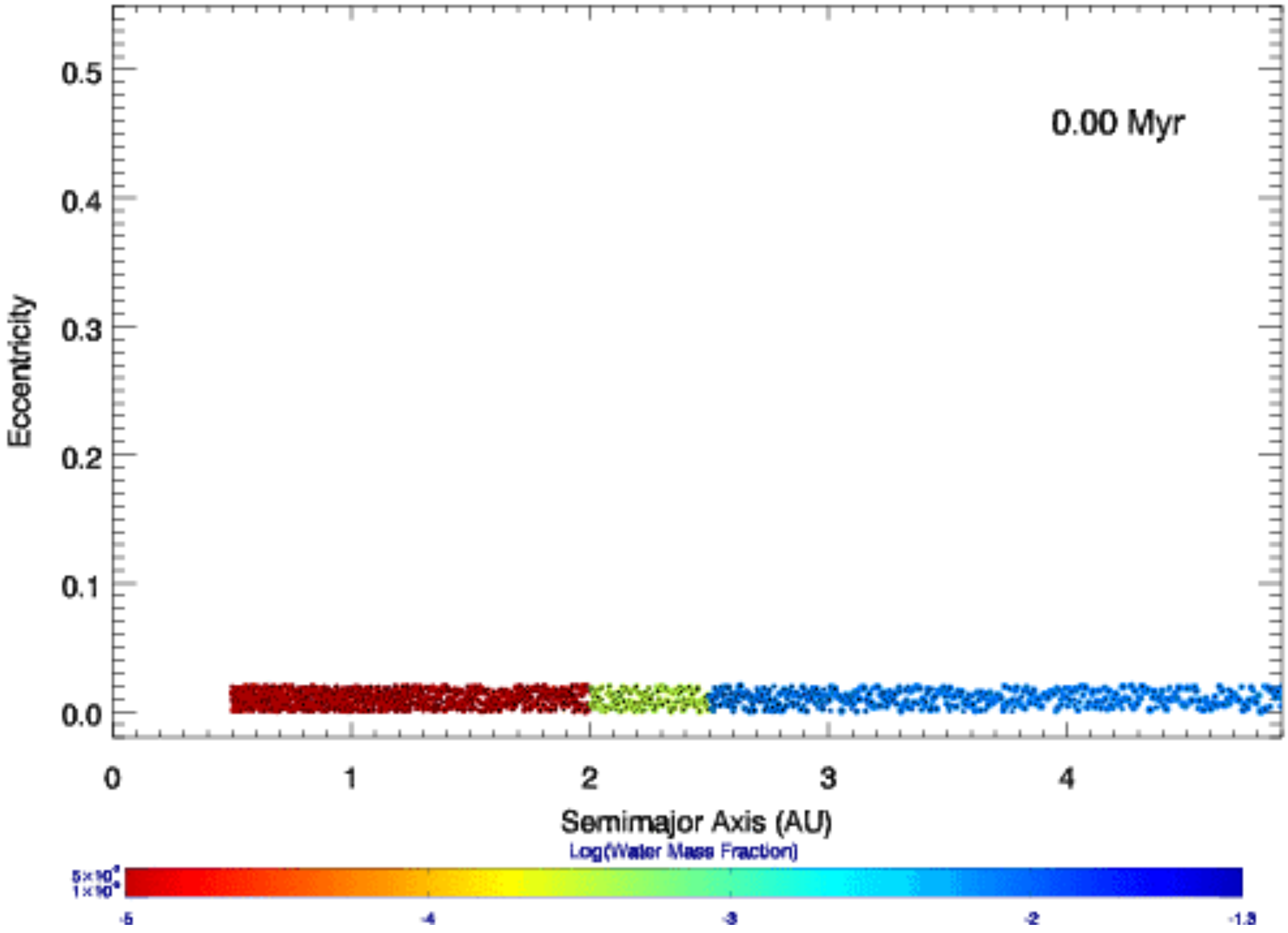
Marty & Yokochi 2006

Type 1 migration

- Important for ~Earth-sized planets that form quickly (Goldreich & Tremaine 1980; Ward 1986; Tanaka et al 2002)
- Another type of "water delivery" (Kuchner 2003)
  – Can lead to close-in water-rich planets (Terquem & Papaloizou 2007; Ogihara & Ida 2009)
- Testable with transit observations (papers by Selsis, Sotin, Seager, Valencia, Fortney, …)
  – e.g., Corot-7b vs GJ 1214b



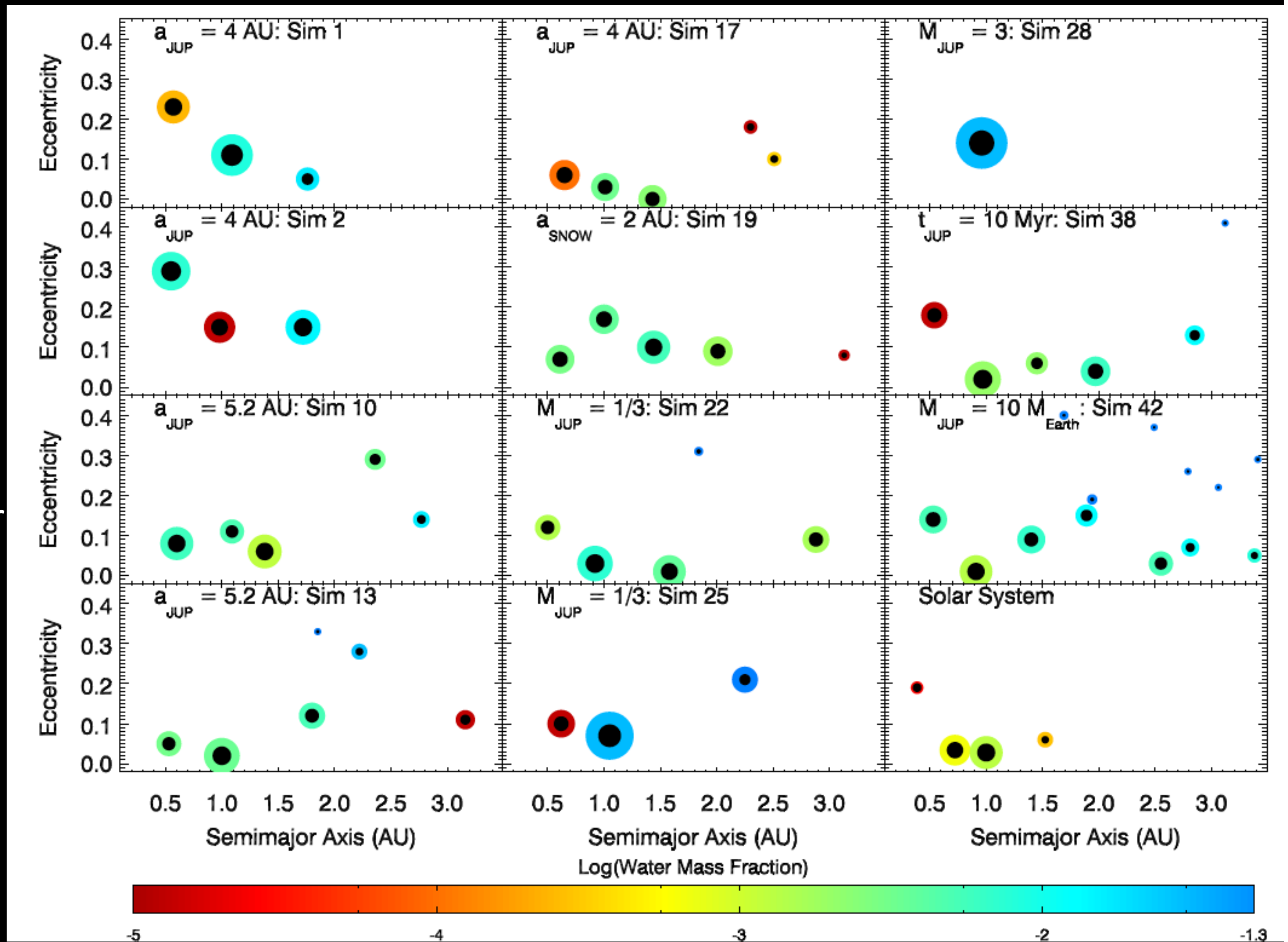
Credit: Phil Armitage



Raymond, Quinn & Lunine 2006

Water delivery

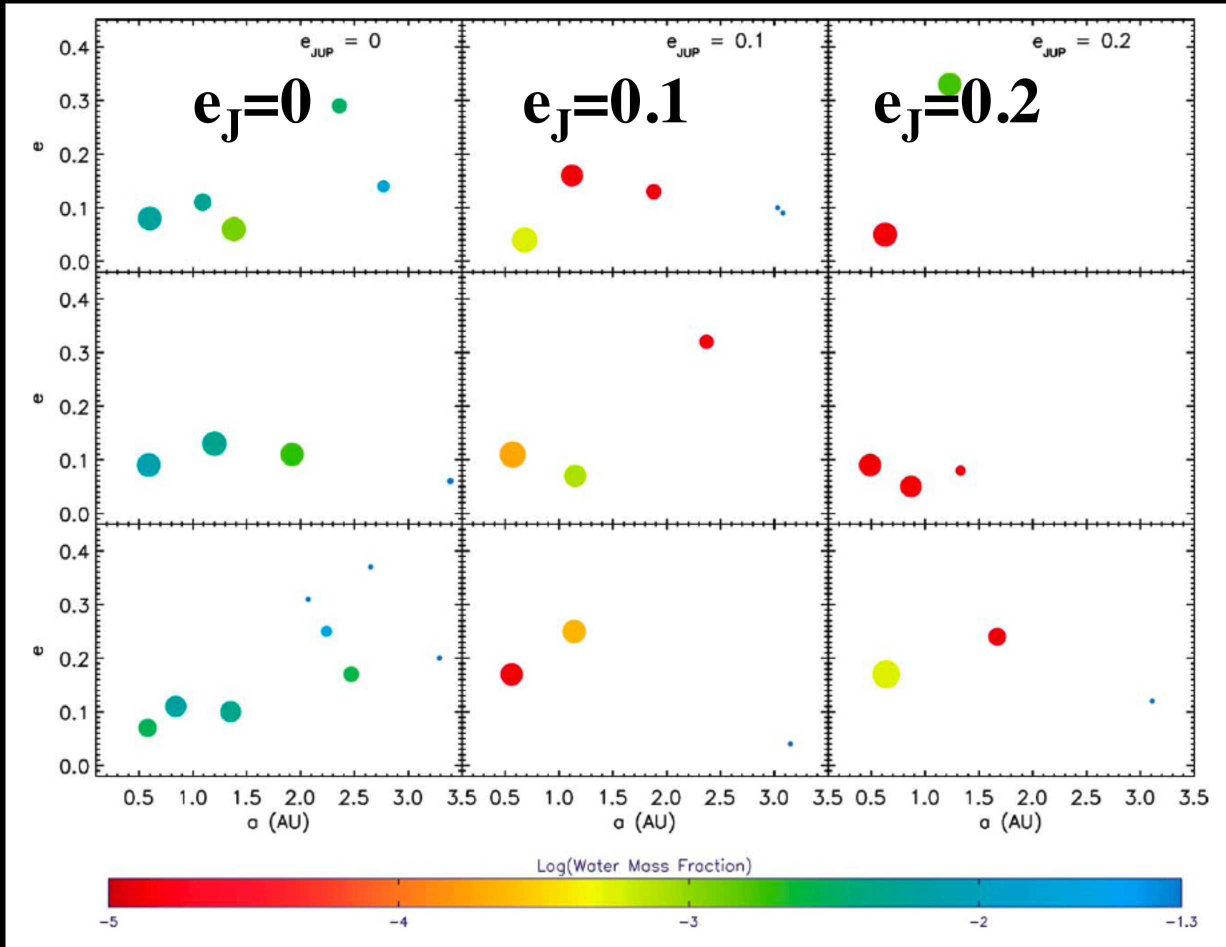
- Stochastic variations during late-stage accretion
(e.g., Quintana & Lissauer 2007, Chambers 2001)



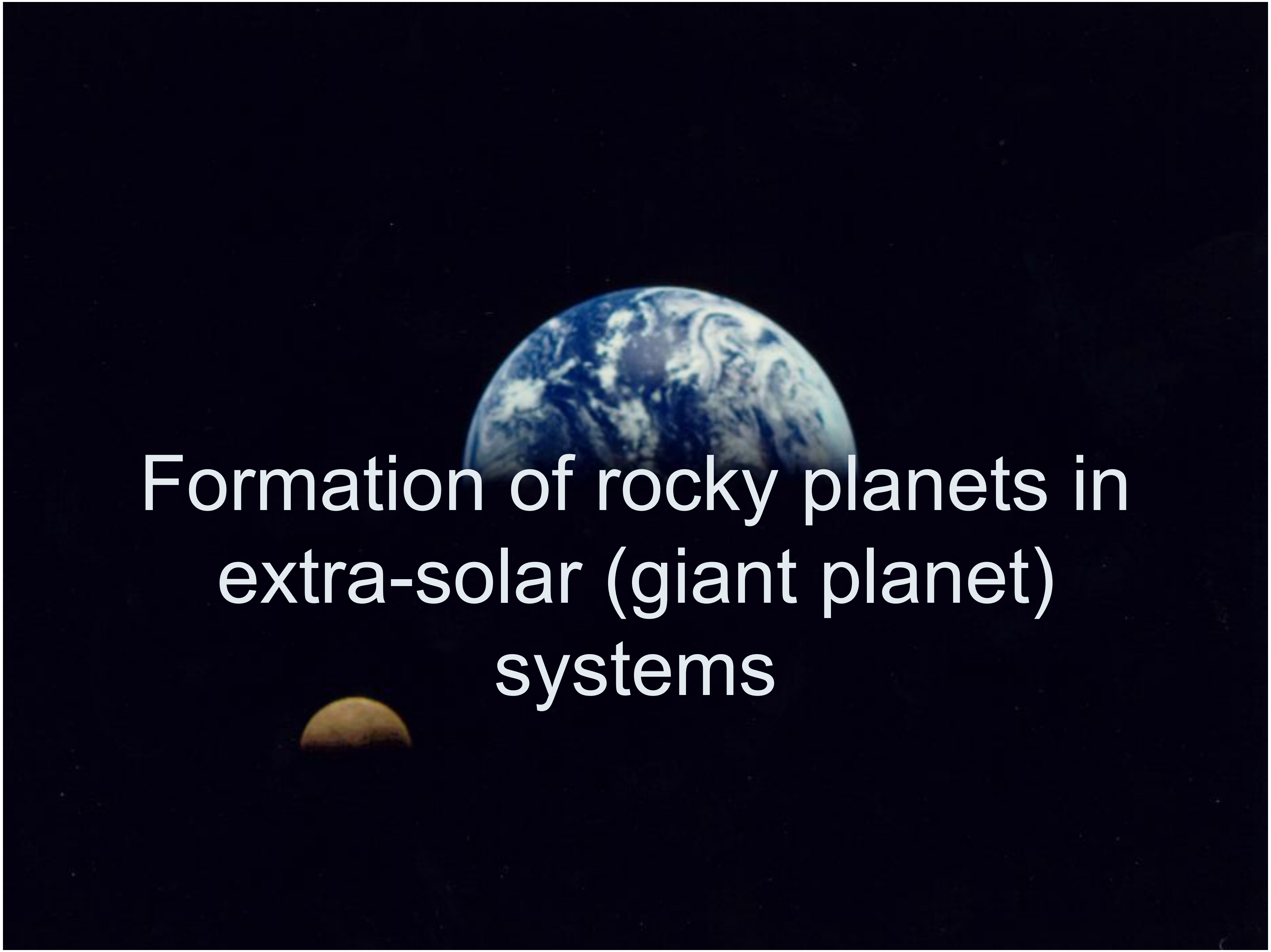
Raymond, Quinn & Lunine 2004

Water delivery

- Water delivery increases systematically for
  – Circular giant planet orbits
    (Chambers & Cassen 2002)
  – Massive disks
    (Raymond, Scalo & Meadows 2007)



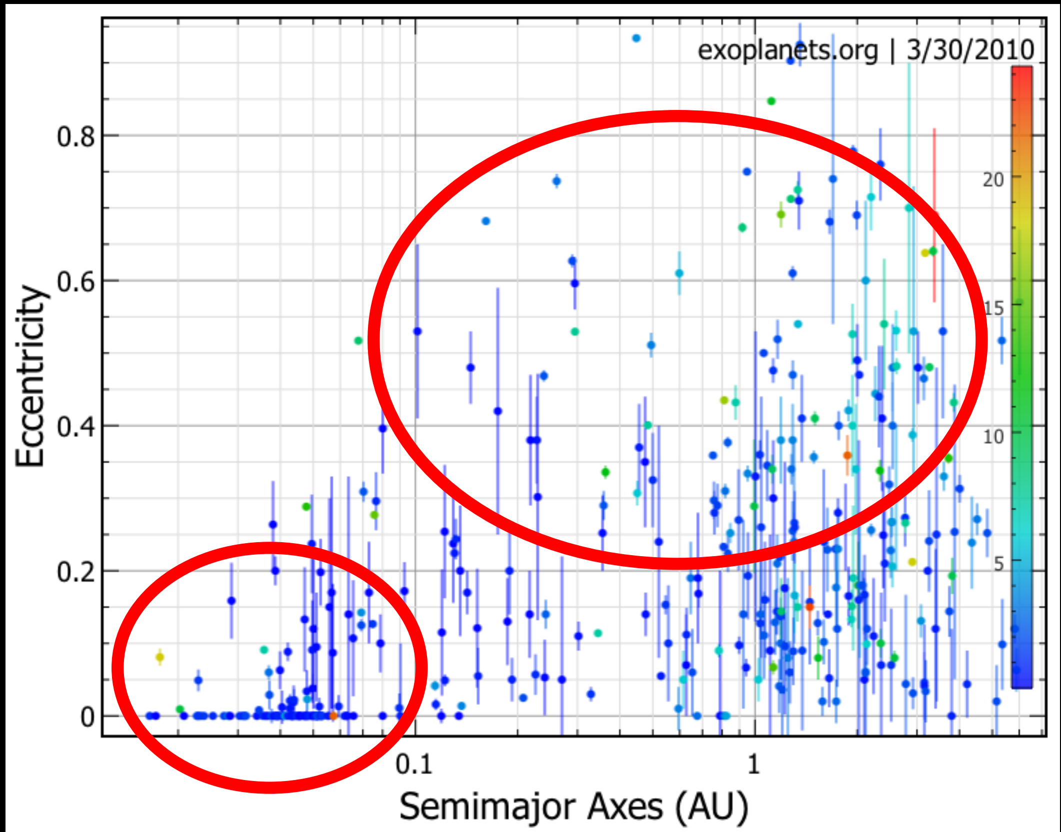
Raymond, Quinn & Lunine 2004


Formation of rocky planets in
extra-solar (giant planet)
systems

Extra-solar (giant) planets

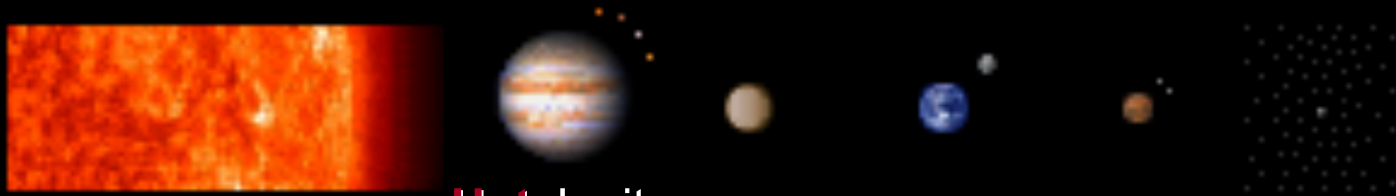
Two key processes have shaped the exoplanet distribution:

1. Orbital (type 2) migration: hot Jupiters, hot Neptunes
2. Planet-planet scattering: large orbital eccentricities



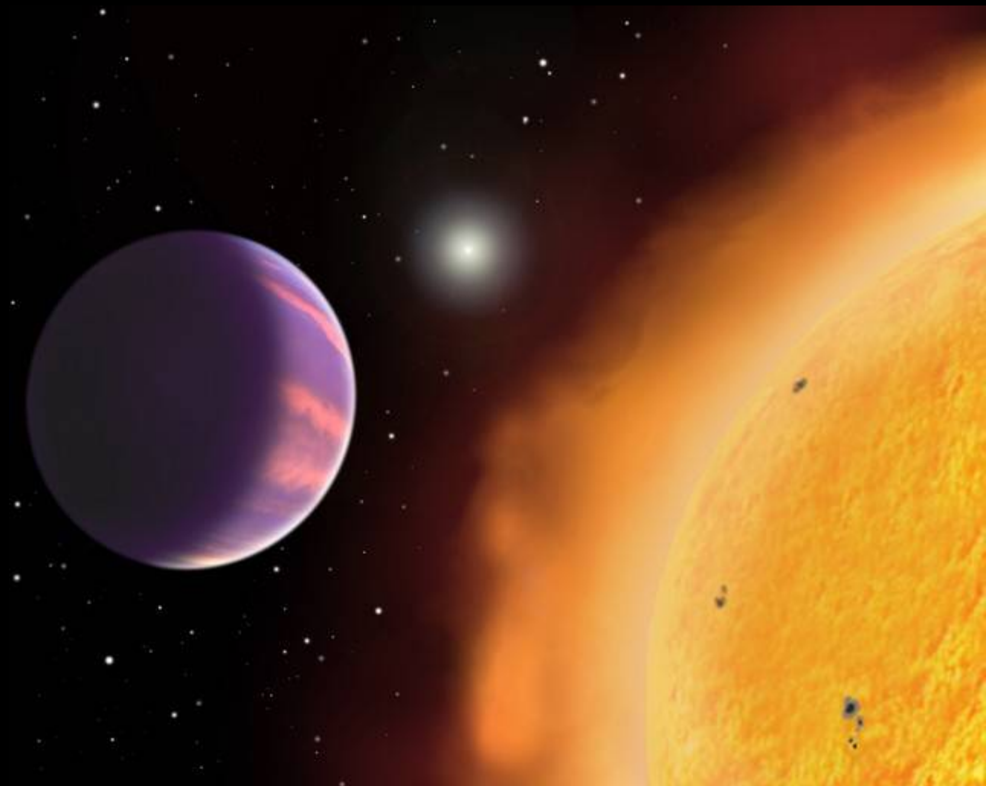
exoplanets.org

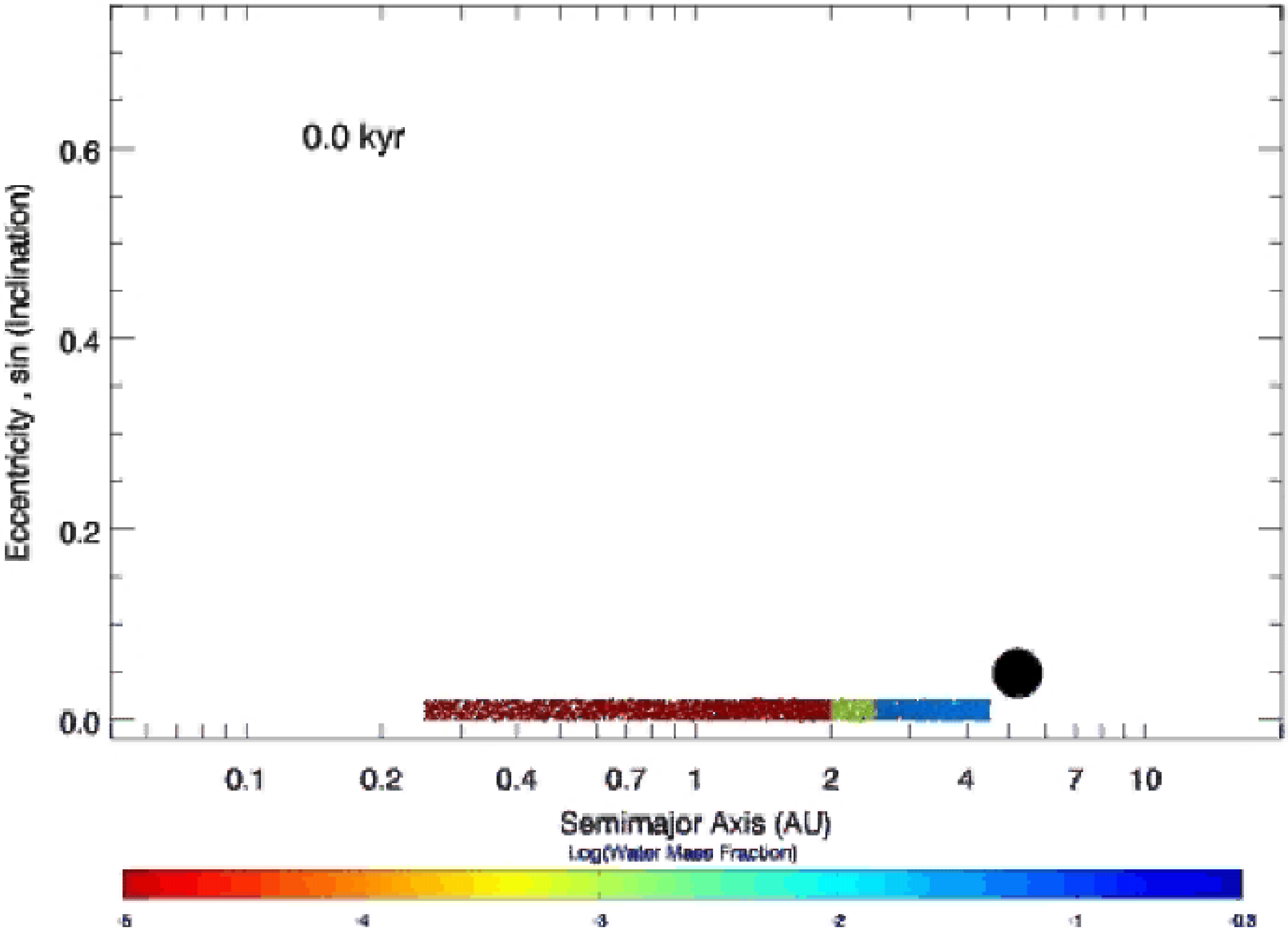
1. Giant Planet Migration



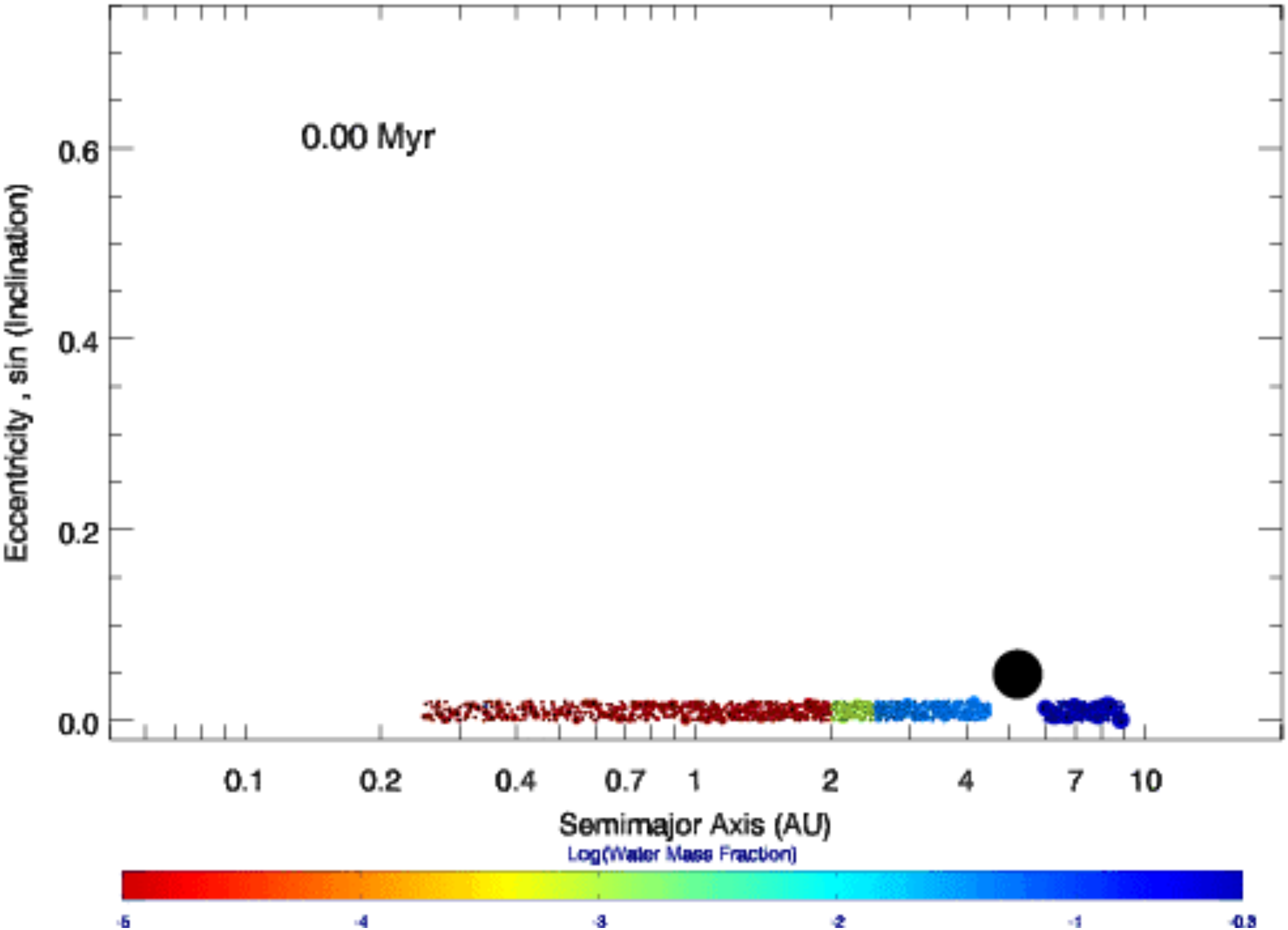
Hot Jupiter　　Jupiter

Close-in giant planets are thought to have migrated to their current locations because of interactions with the protoplanetary disk. How does this affect terrestrial planet formation?





Raymond, Mandell & Sigurdsson 2006



Raymond, Mandell & Sigurdsson 2006; Mandell, Raymond & Sigurdsson 2007

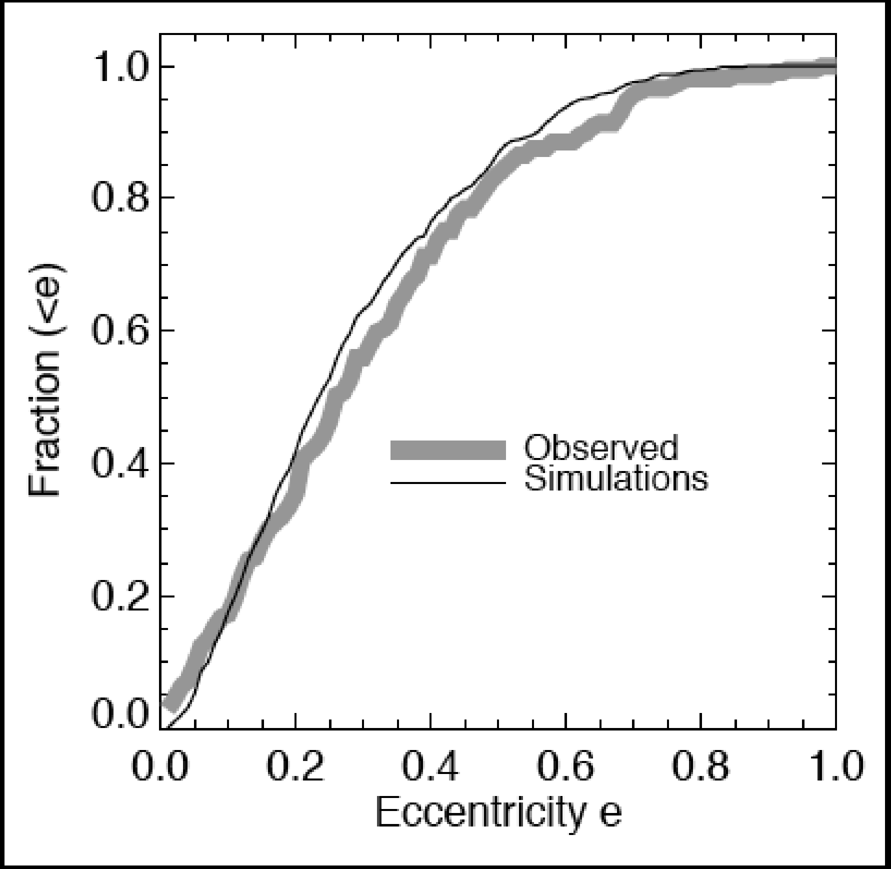

Credit: Nahks Tr’Enhl

2. Planet-planet scattering

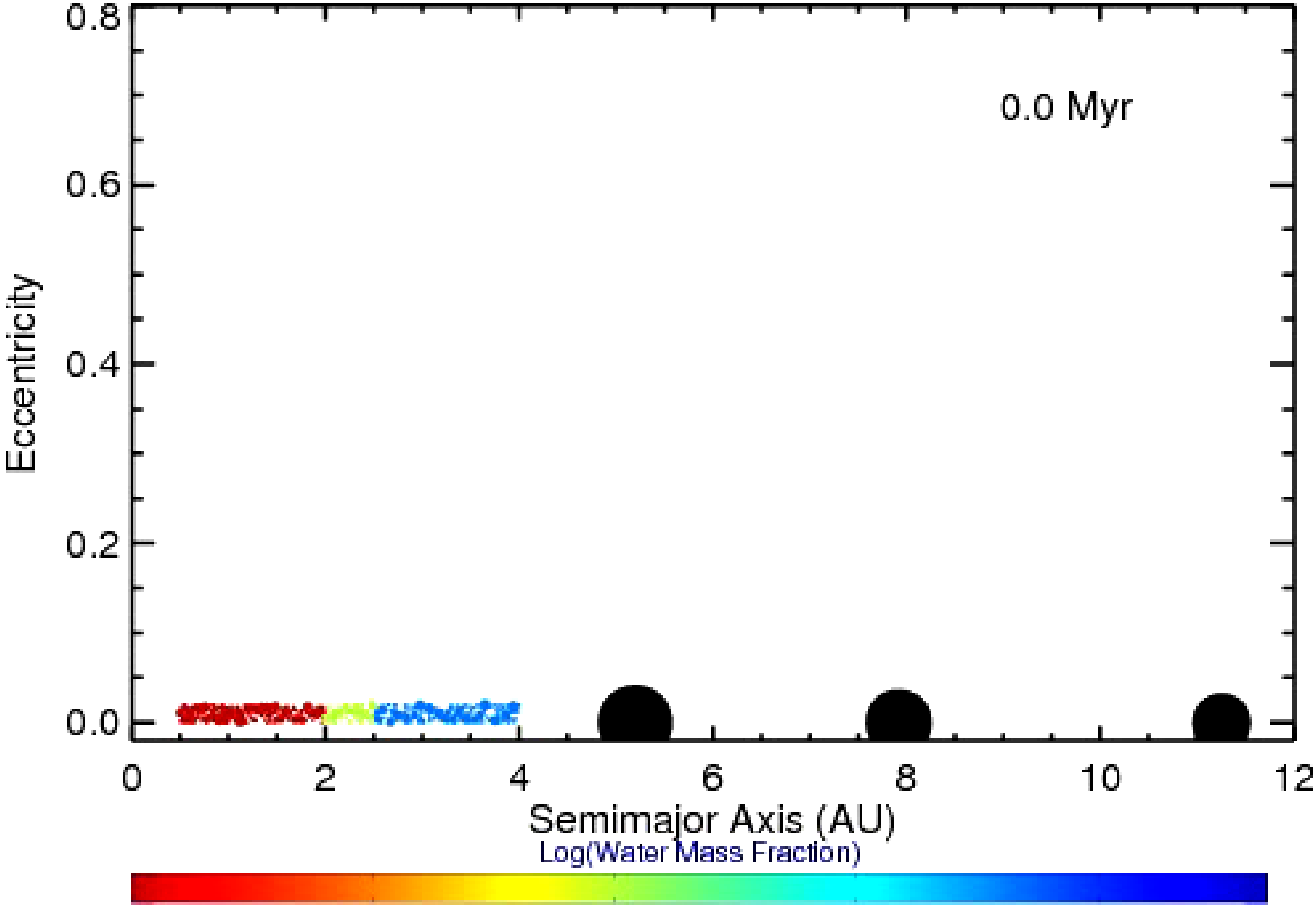
Dynamical instabilities leading to scattering can reproduce the observed exoplanet eccentricity distribution with virtually zero assumptions

(Chatterjee et al 2008; Ford & Rasio 2008; Adams & Laughlin 2003; Juric & Tremaine 2008; Marzari & Weidenschilling 2002)

Poster by Malmberg, talks by Armitage, Thommes

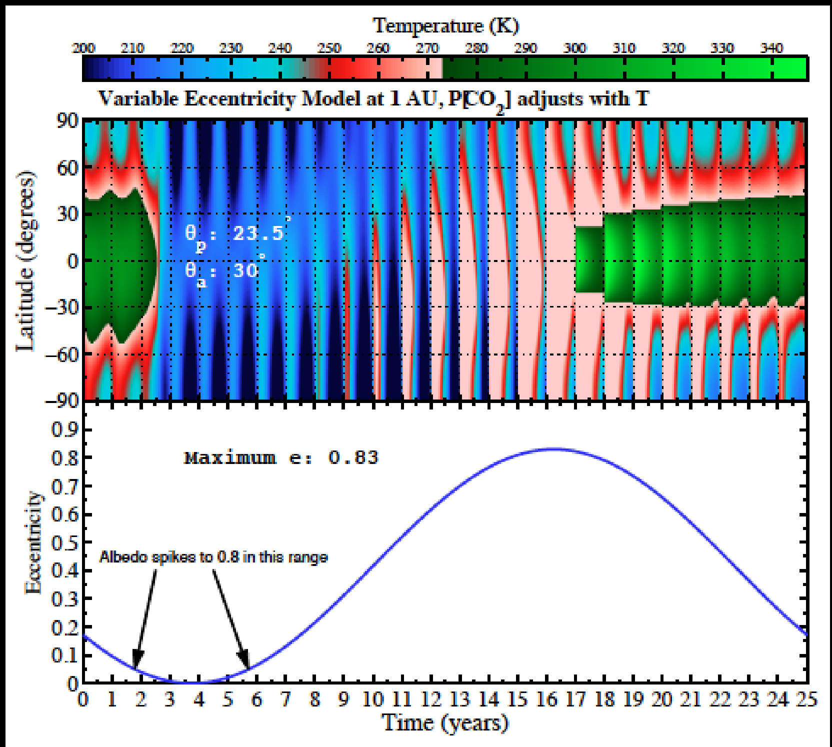


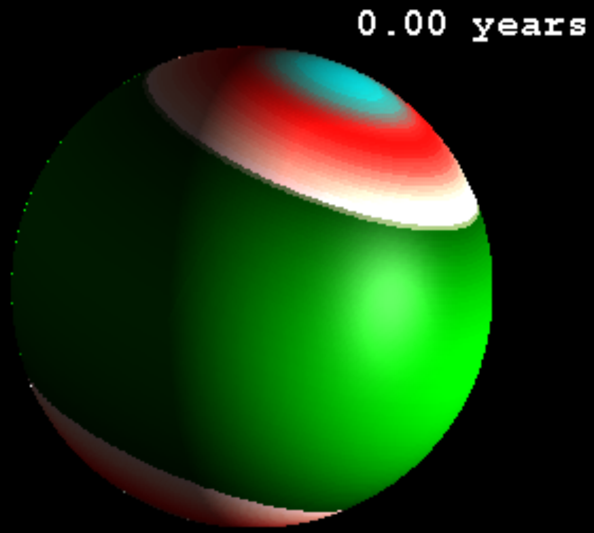
Raymond, Armitage, & Gorelick 2009

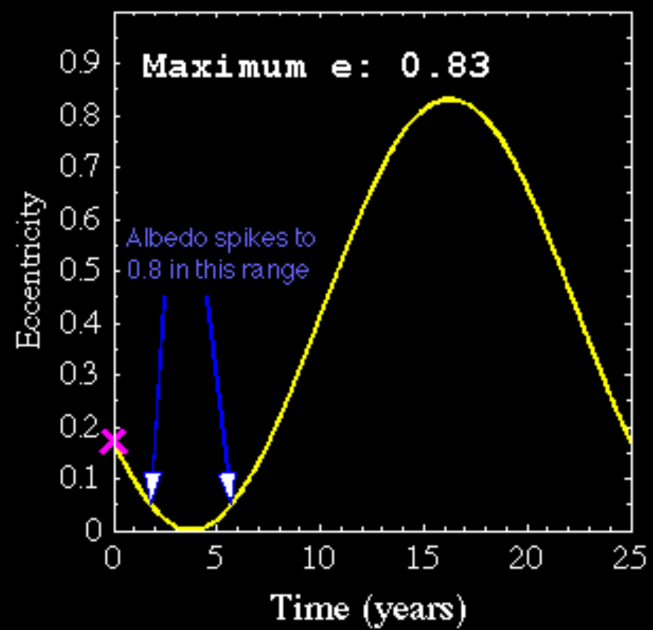


Raymond, Armitage et al 2010

Climate model with oscillating eccentricity



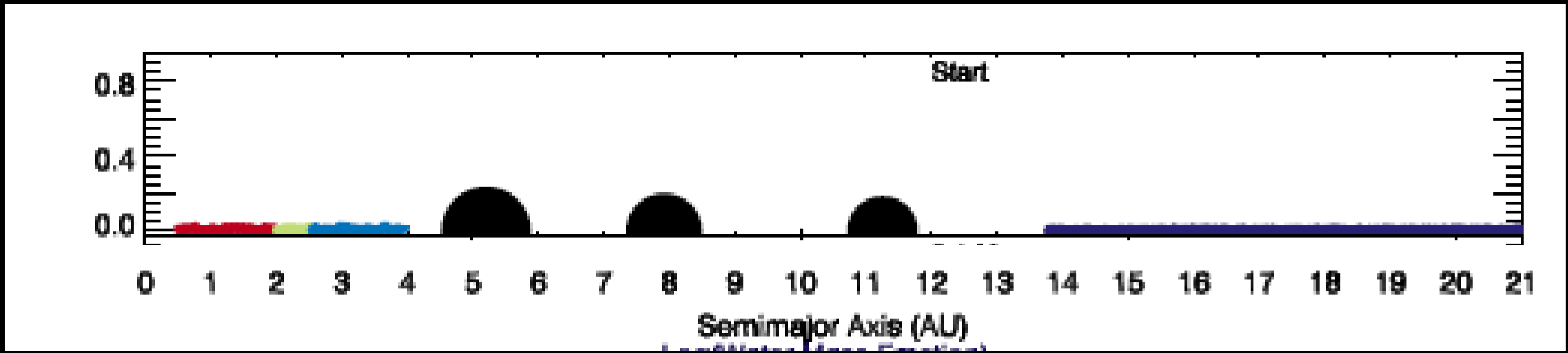




Spiegel et al 2010

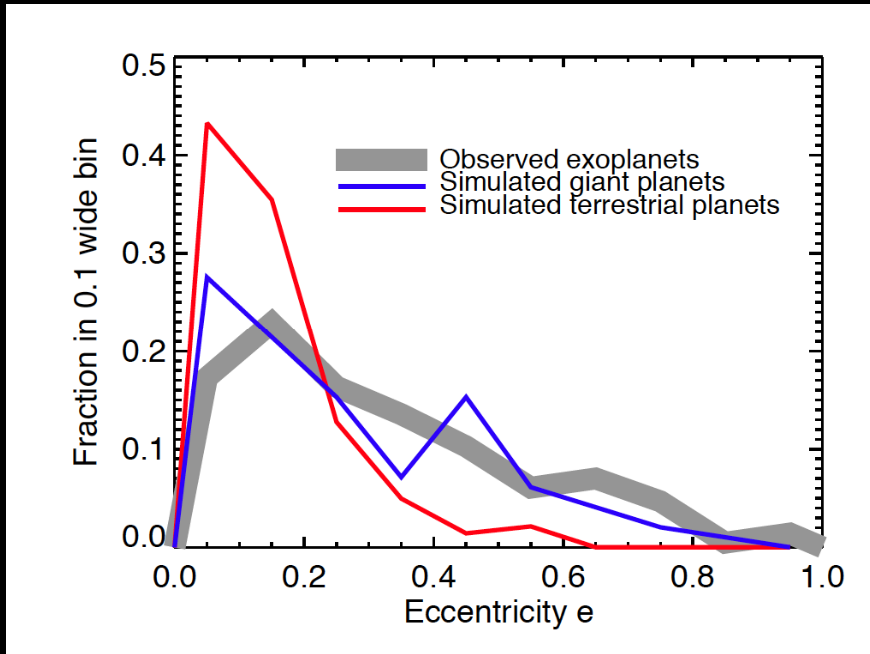
A simple experiment

- Run simulations with:
  - Terrestrial embryos+planetesimals
  - 3 giant planets
  - Outer disk of planetesimals



A simple experiment

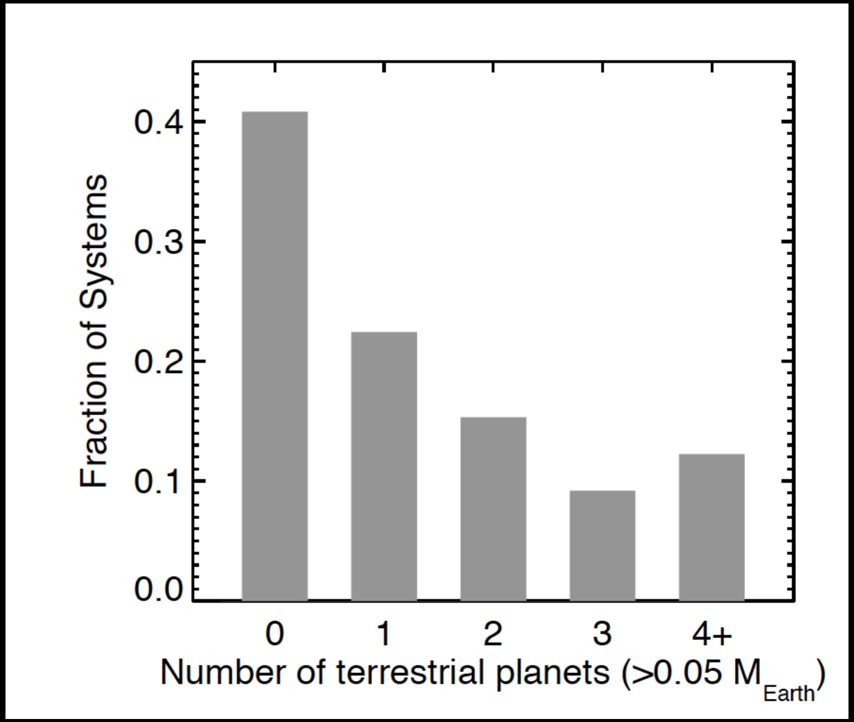
- Match the giant planet eccentricity distribution



Surviving terrestrial planets have lower mean ecc than giants

A simple experiment

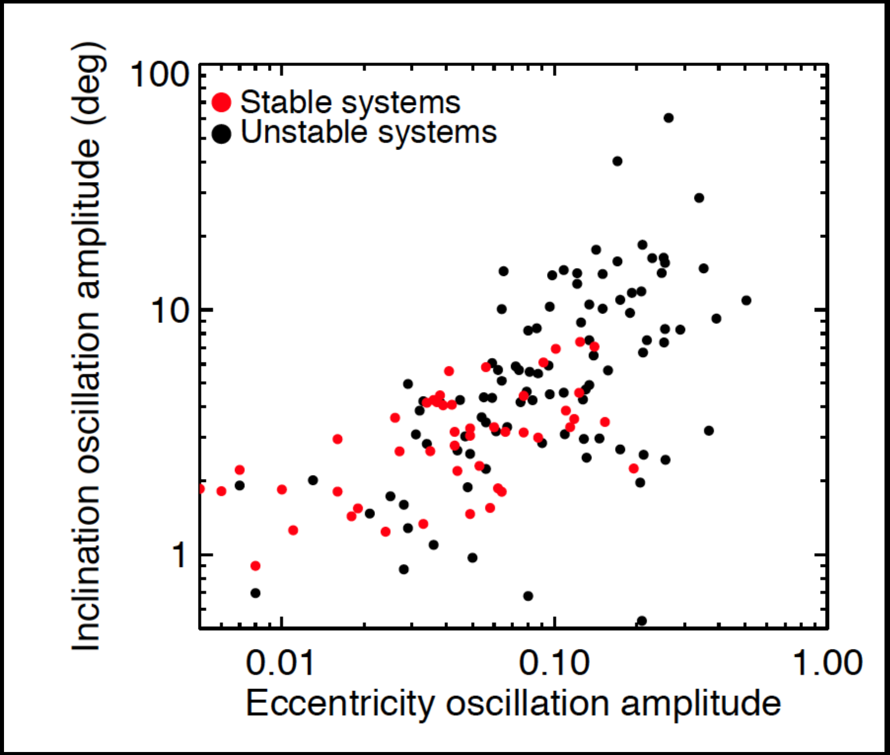
- Match the giant planet eccentricity distribution
- Look at resulting terrestrial planet properties



Many systems have destroyed their terrestrial planets

A simple experiment

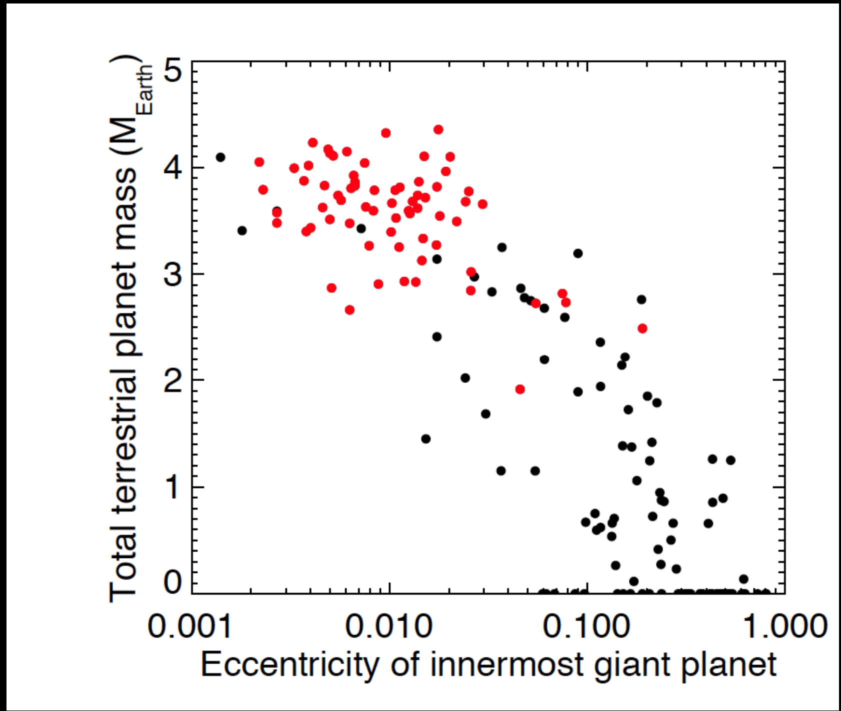
- Match the giant planet eccentricity distribution
- Look at resulting terrestrial planet properties



Large oscillations in e and i are common: important for the climate (Spiegel et al 2010)

A simple experiment

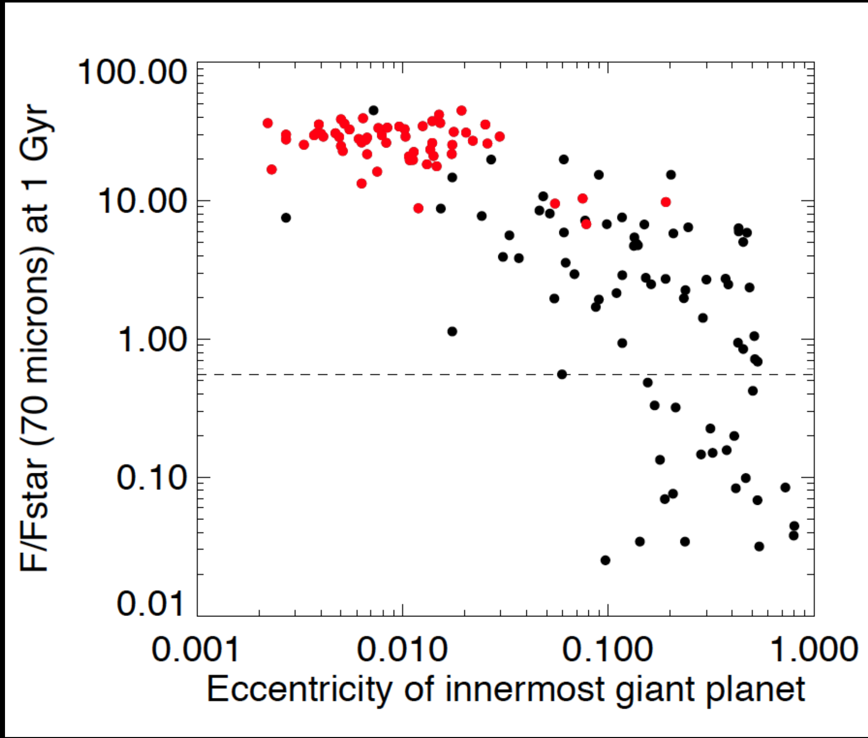
- Match the giant planet eccentricity distribution
- Look at resulting terrestrial planet properties



Low eccentricity giant planets correlate with well-developed terrestrial planet systems (e.g., Levison & Agnor 2003)

A simple experiment

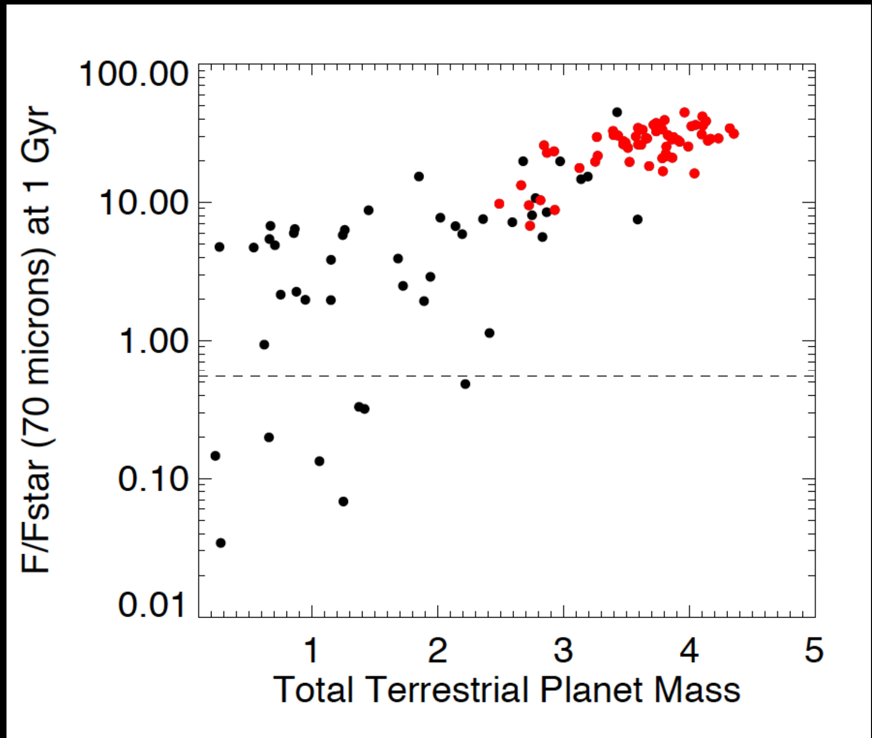
- Match the giant planet eccentricity distribution
- Look at resulting terrestrial planet properties
- Link to observable dust production from planetesimal collisions



High-eccentricity giant planets destroy planetesimals and observable dust

A simple experiment

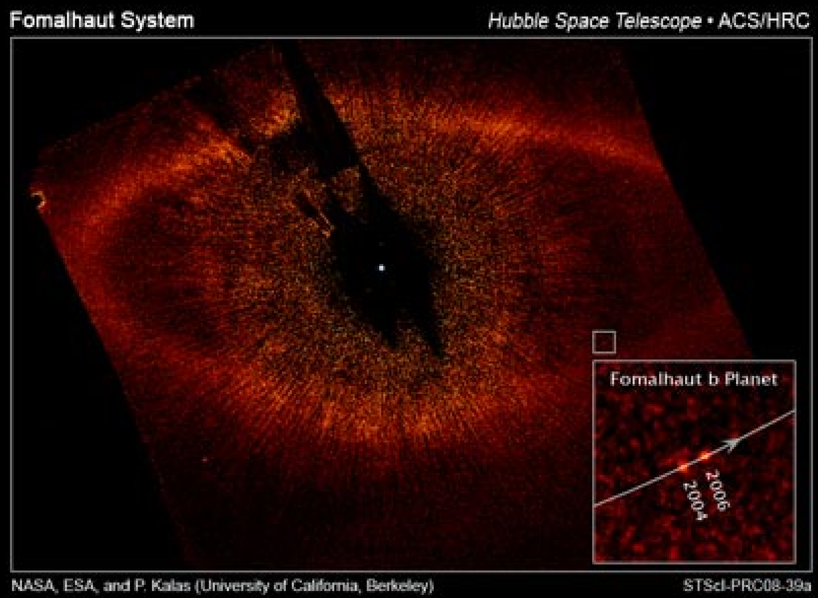
- Match the giant planet eccentricity distribution
- Look at resulting terrestrial planet properties
- Link to observable dust production from planetesimal collisions



Strong correlation between cold dust and large terrestrial planets

Speculation

- Old systems with lots of cold dust are good candidates for terrestrial planets
- 15-20% of old stars have bright cold dust (Trilling et al 2008; Carpenter et al 2009) -- a lower limit for eta_Earth?



Kalas et al 2008

Collaborators

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- Avi Mandell (NASA Goddard)
- David Spiegel (Princeton)
- Tom Quinn (Washington)
- Jonathan Lunine (Arizona)
- John Scalo (Texas)
- Vikki Meadows (Washington)
- Mark Booth (Cambridge)
- Mark Wyatt (Cambridge)
- Phil Armitage (Colorado)
- Alessandro Morbidelli (Nice)
- David O'Brien (PSI)
- Eric Gaidos (Hawaii)
- Nate Kaib (Washington)
- Steinn Sigurdsson (Penn St.)
- Amaya Moro-Martin (Madrid)
- John Armstrong (Weber St)
- Franck Selsis (Bordeaux)

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