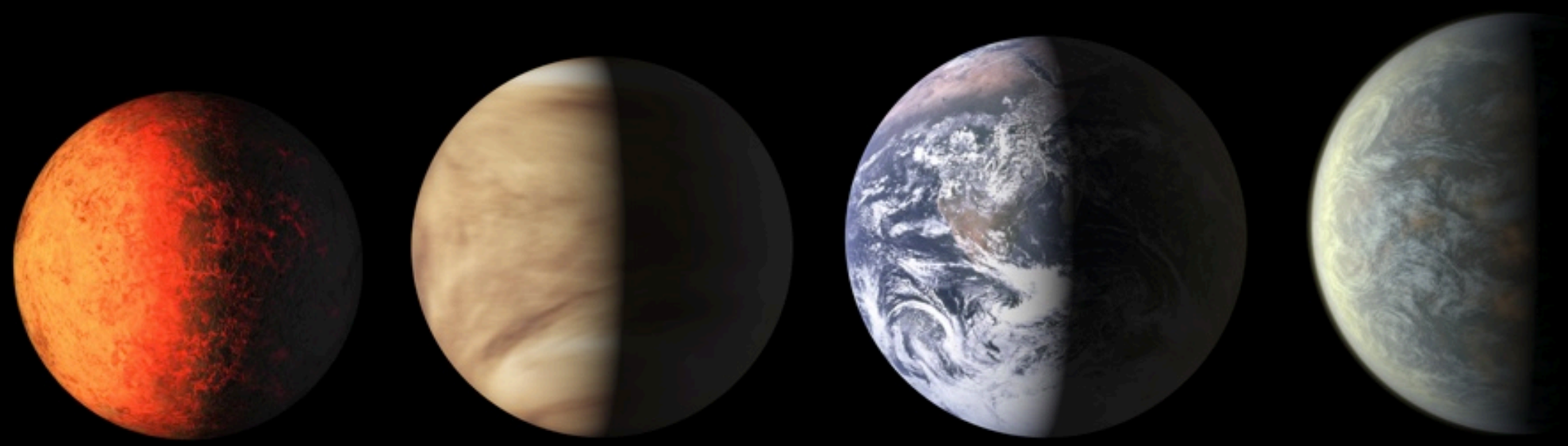
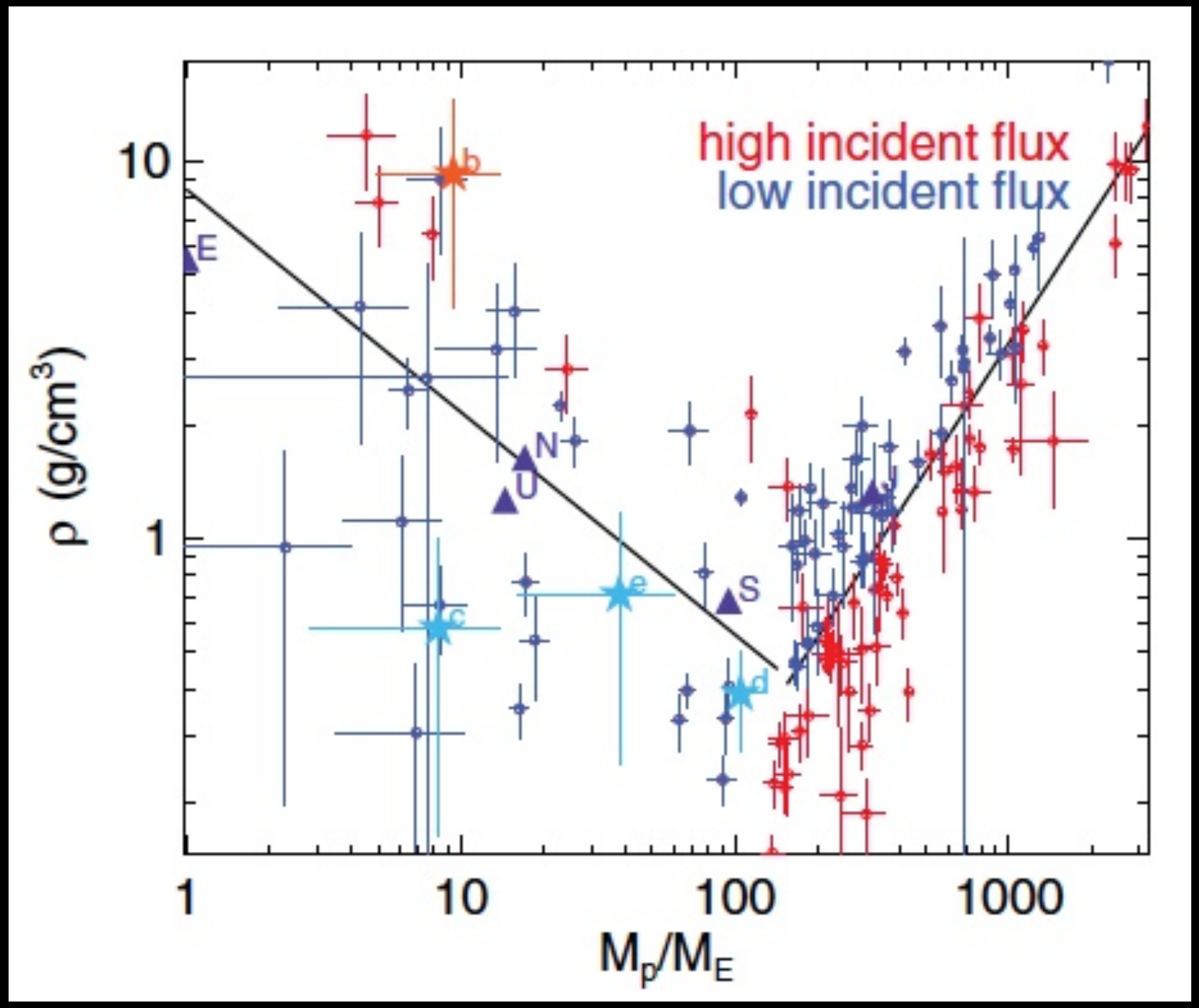
Terrestrial planet formation at home and abroad



Sean Raymond (Obs. de Bordeaux, France)
Eiichiro Kokubo (NAOJ, Japan)
Alessandro Morbidelli (Obs. de Nice, France)
Ryuji Morishima (JPL, Caltech, USA)
Kevin Walsh (SwRI, Boulder, USA)

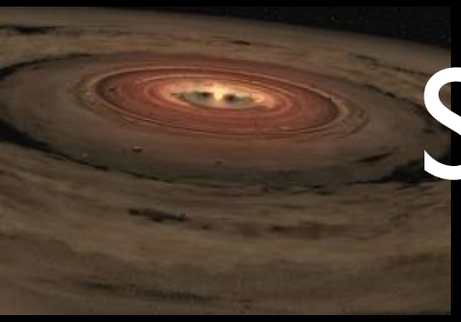
Image credit: NASA/Ames/JPL-Caltech

“Terrestrial” planets



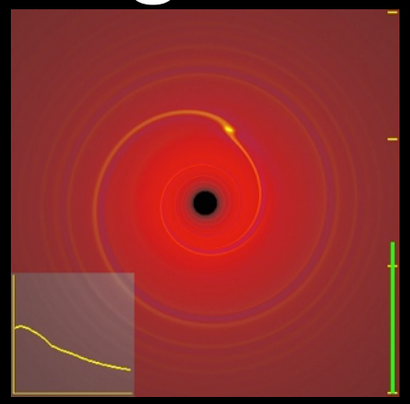
Weiss et al 2013, ApJ, 768, 14.

Stages of Planet Formation



Grains

Type I migration



Planetesimals

Planetary Embryos

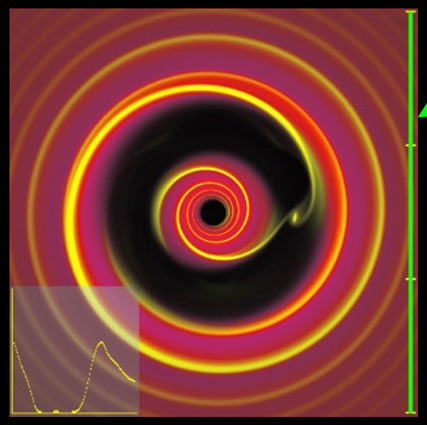
while gas remains

No more gas

INFLUENCE

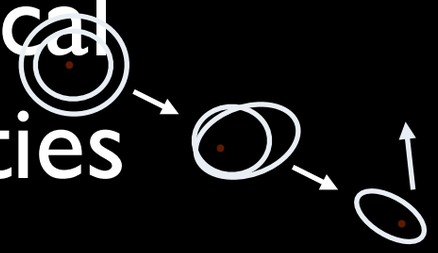
Gaseous Planets

Terrestrial Planets



Type 2 migration

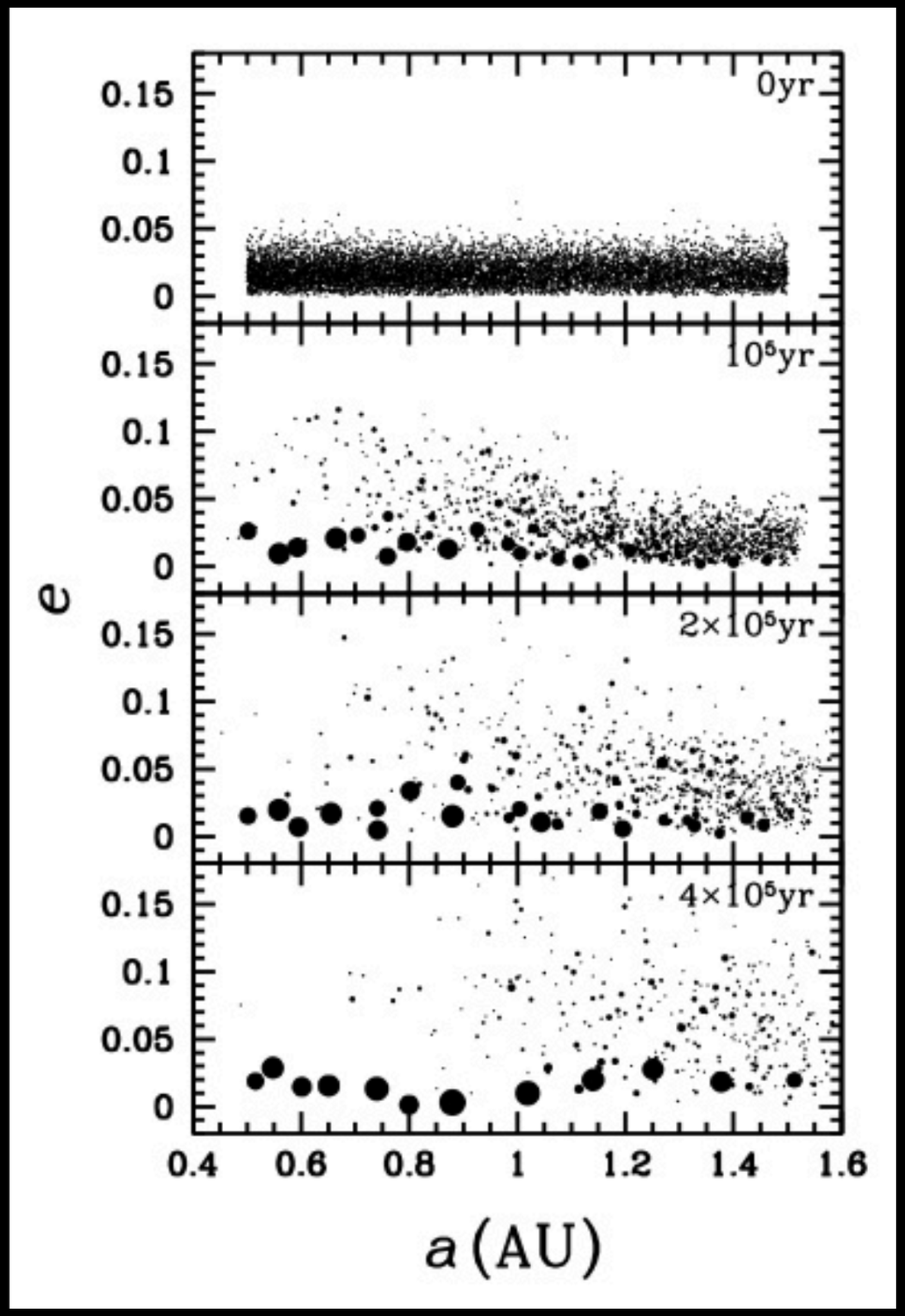
Dynamical instabilities



2 ways to form planetary embryos

From km-sized planetesimals

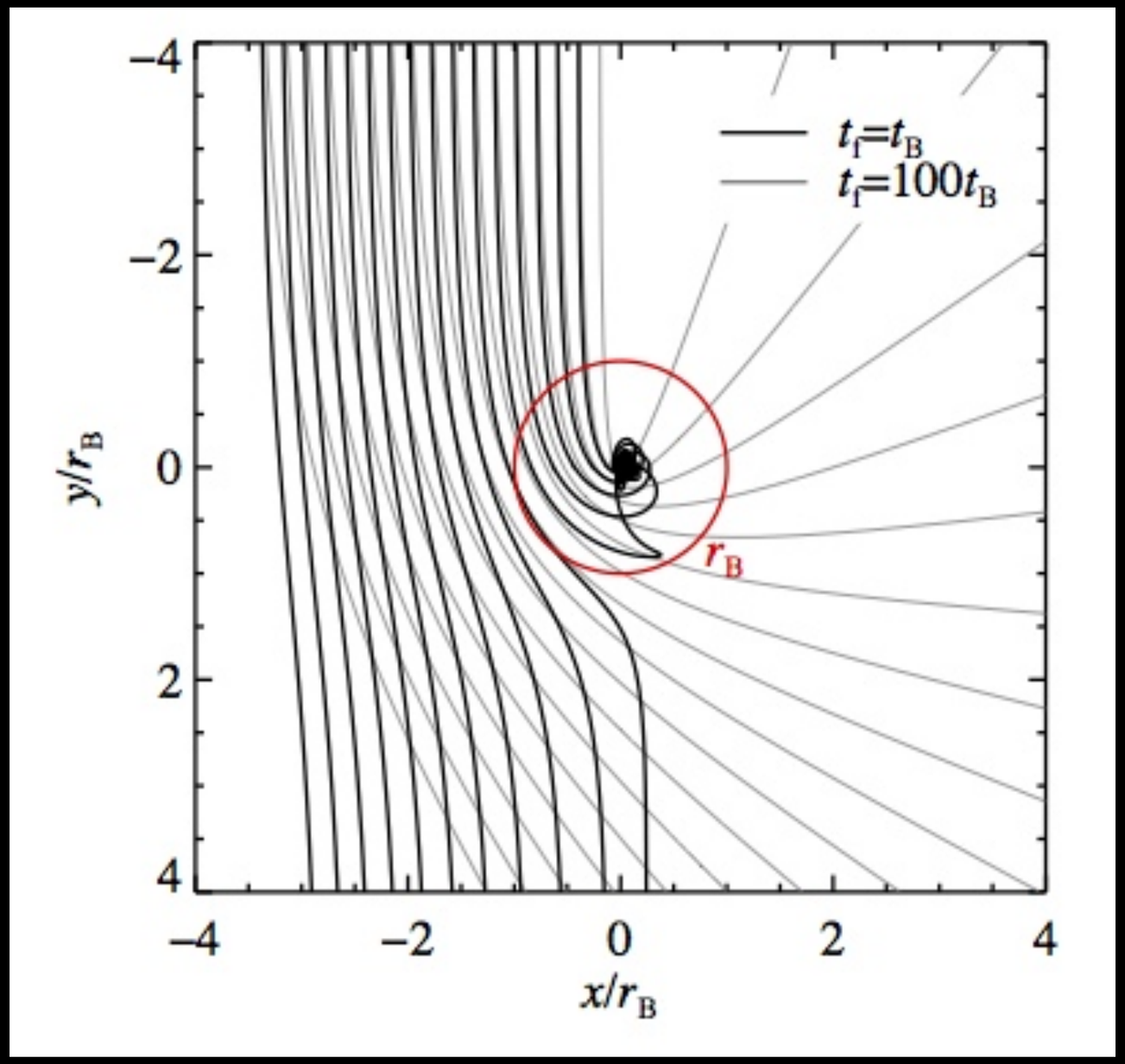
- $dM/dt \sim M^{4/3}$: runaway growth (Greenberg et al 1978; Wetherill & Stewart 1989)
- $dM/dt \sim M^{2/3}$: oligarchic growth (Kokubo & Ida 1998, 2000, 2002)



Kokubo & Ida 1998, Icarus, 131, 171.

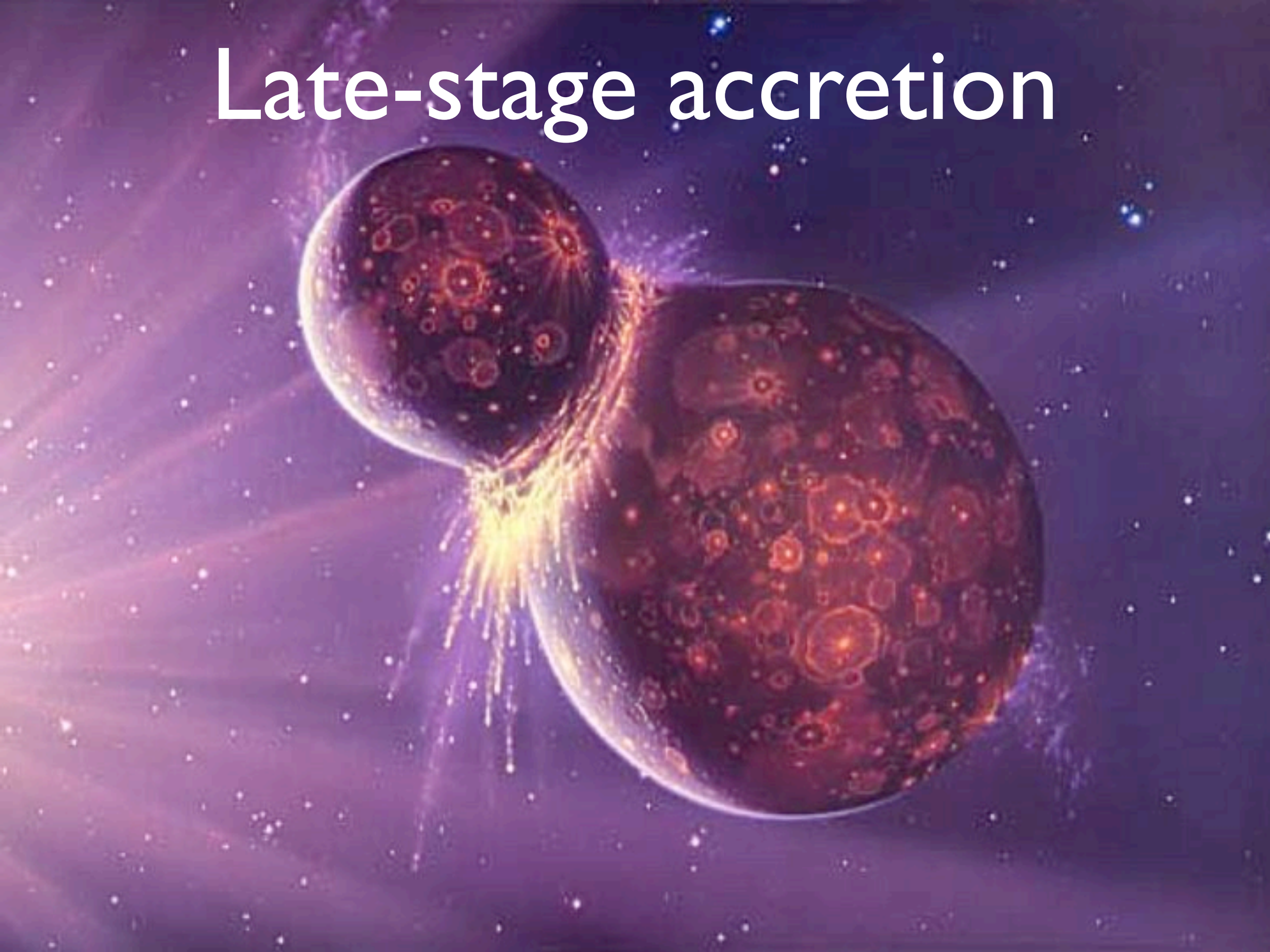
From cm- to dm-sized pebbles

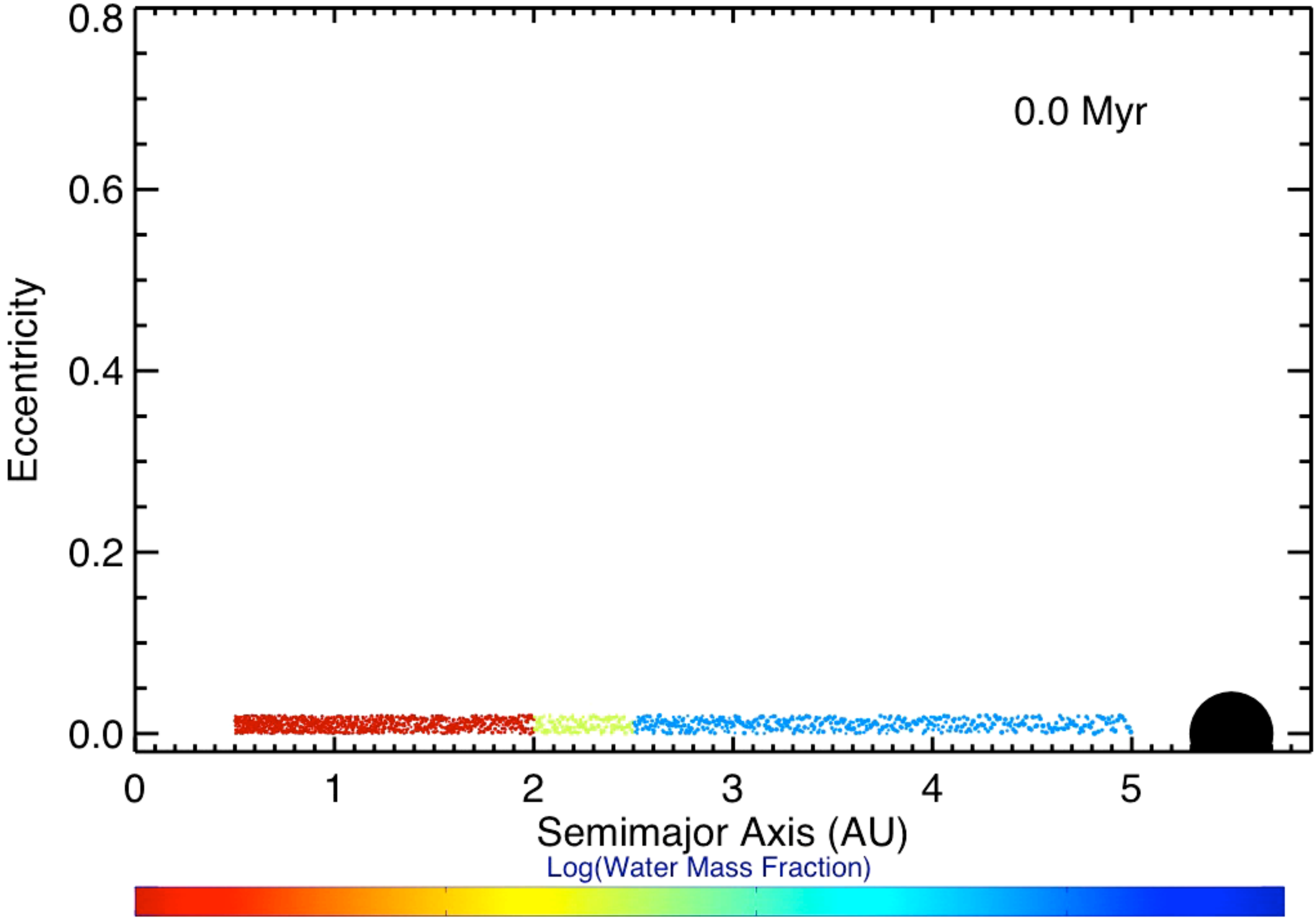
- $dM/dt \sim M^2$: super-runaway growth (Lambrechts & Johansen 2012; Morbidelli & Nesvorny 2012)
- $dM/dt \sim M$ then $M^{2/3}$: oligarchic regime



Lambrechts & Johansen 2012, A&A, 544, A32.

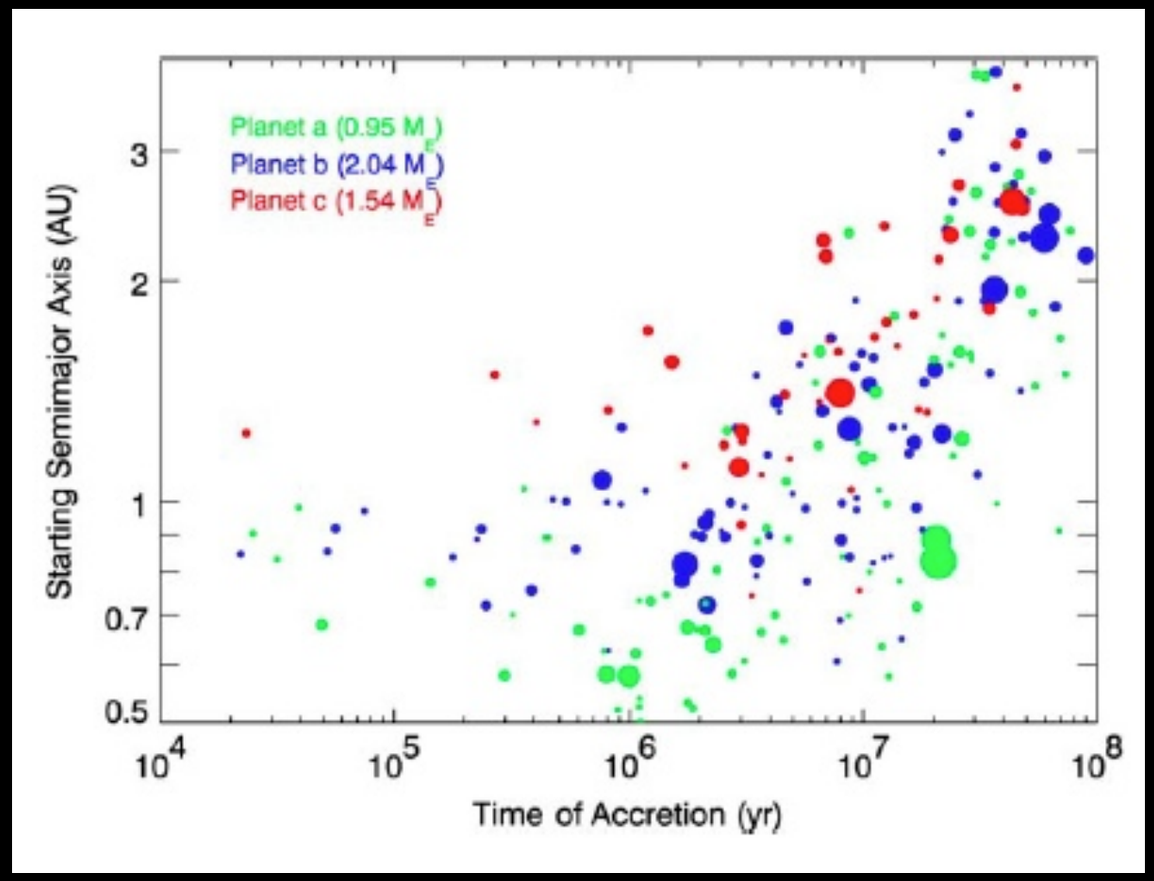
Late-stage accretion



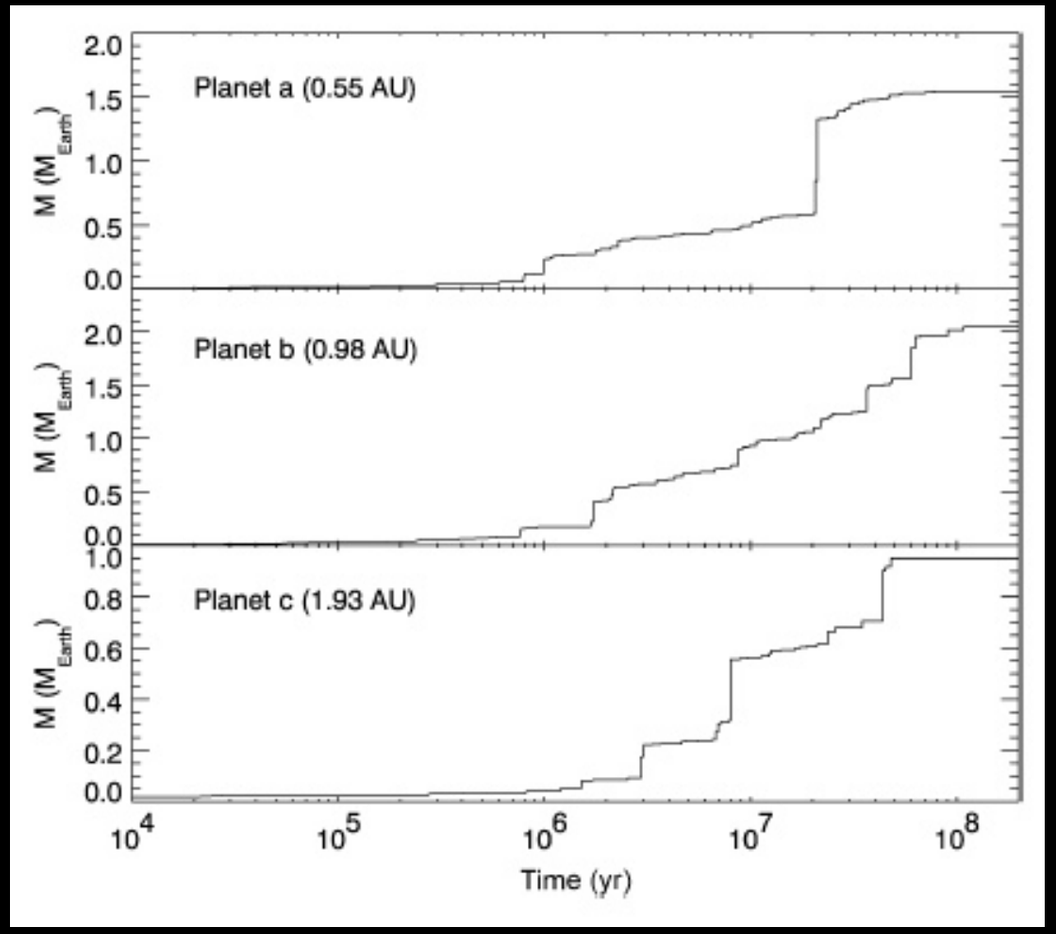


Raymond, Quinn & Lunine 2006, Icarus, 183, 265

- Planets' feeding zones widen and move outward in time



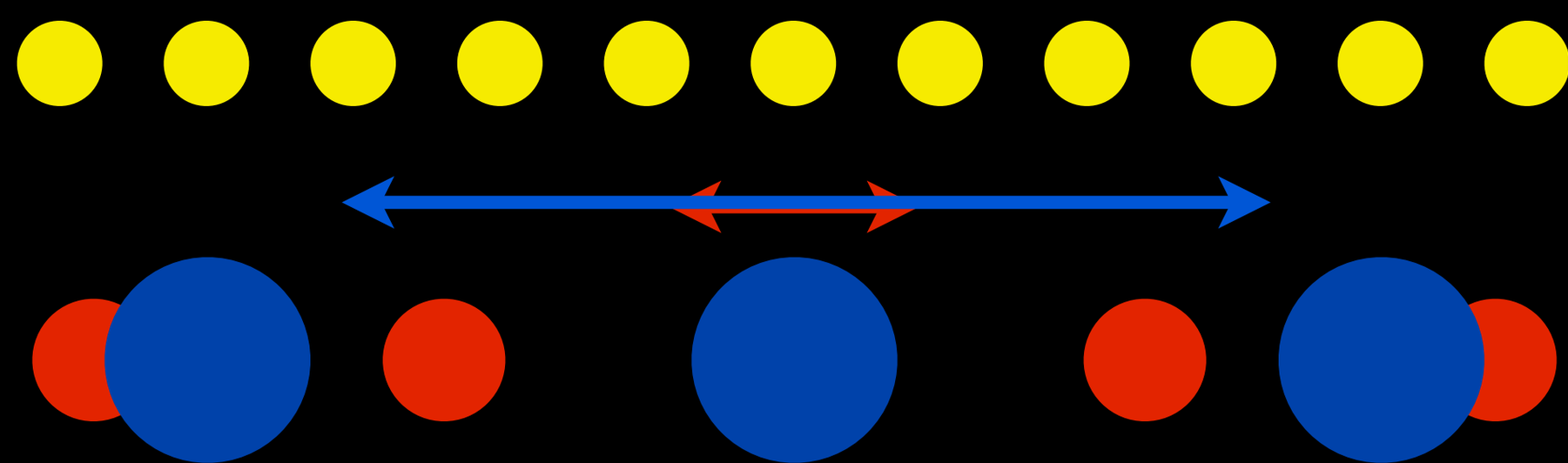
- Impacts are smaller early on, biggest impacts happen late

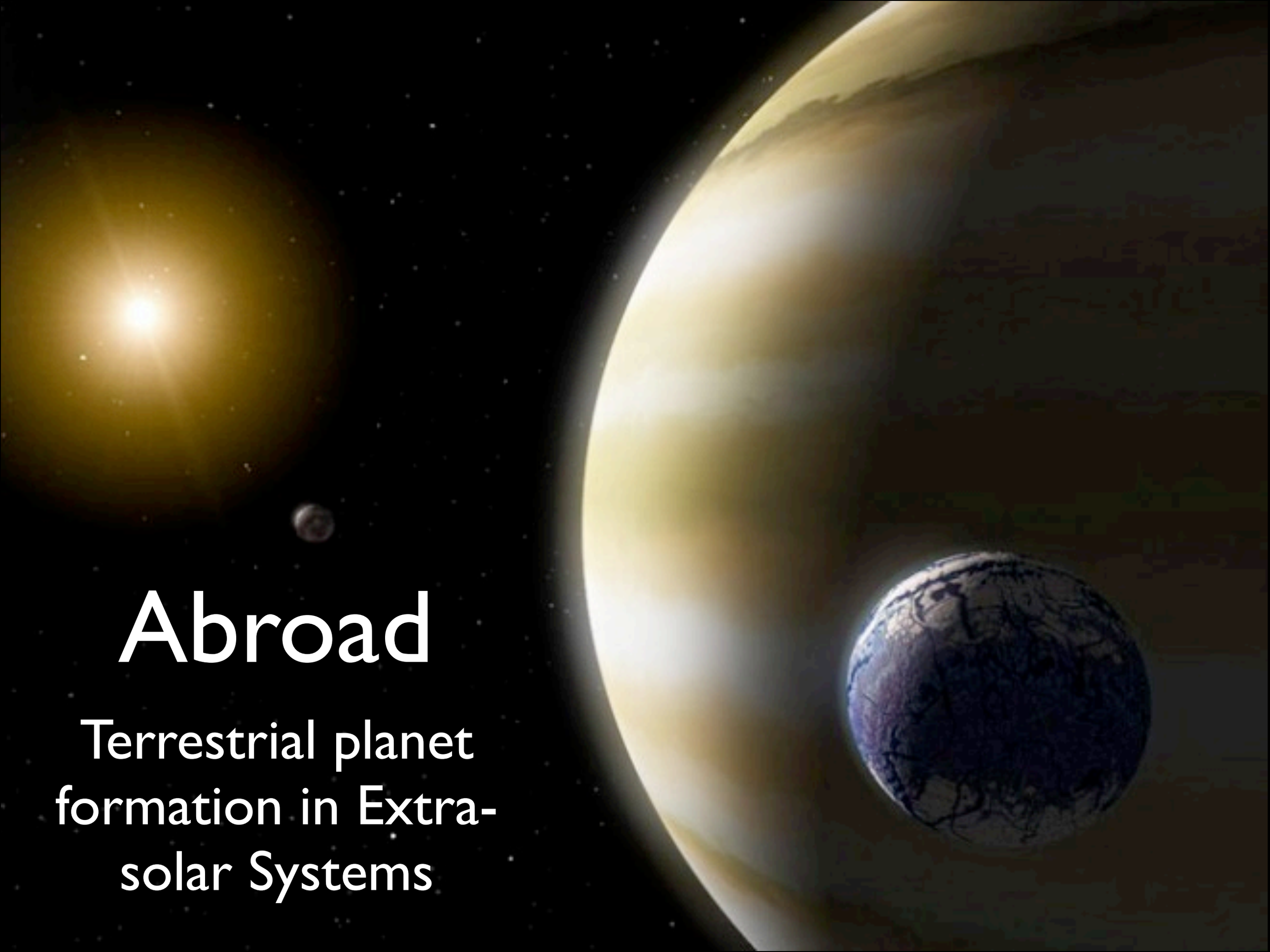


Raymond, Quinn & Lunine 2006, Icarus, 183, 265

Key factors in outcome

- Disk properties: mass, surface density profile (Chambers & Cassen 2002; Raymond et al 2005, 2007; Kokubo et al 2006)
- Degree of eccentricity excitation (Levison & Agnor 2003; Raymond et al 2009)



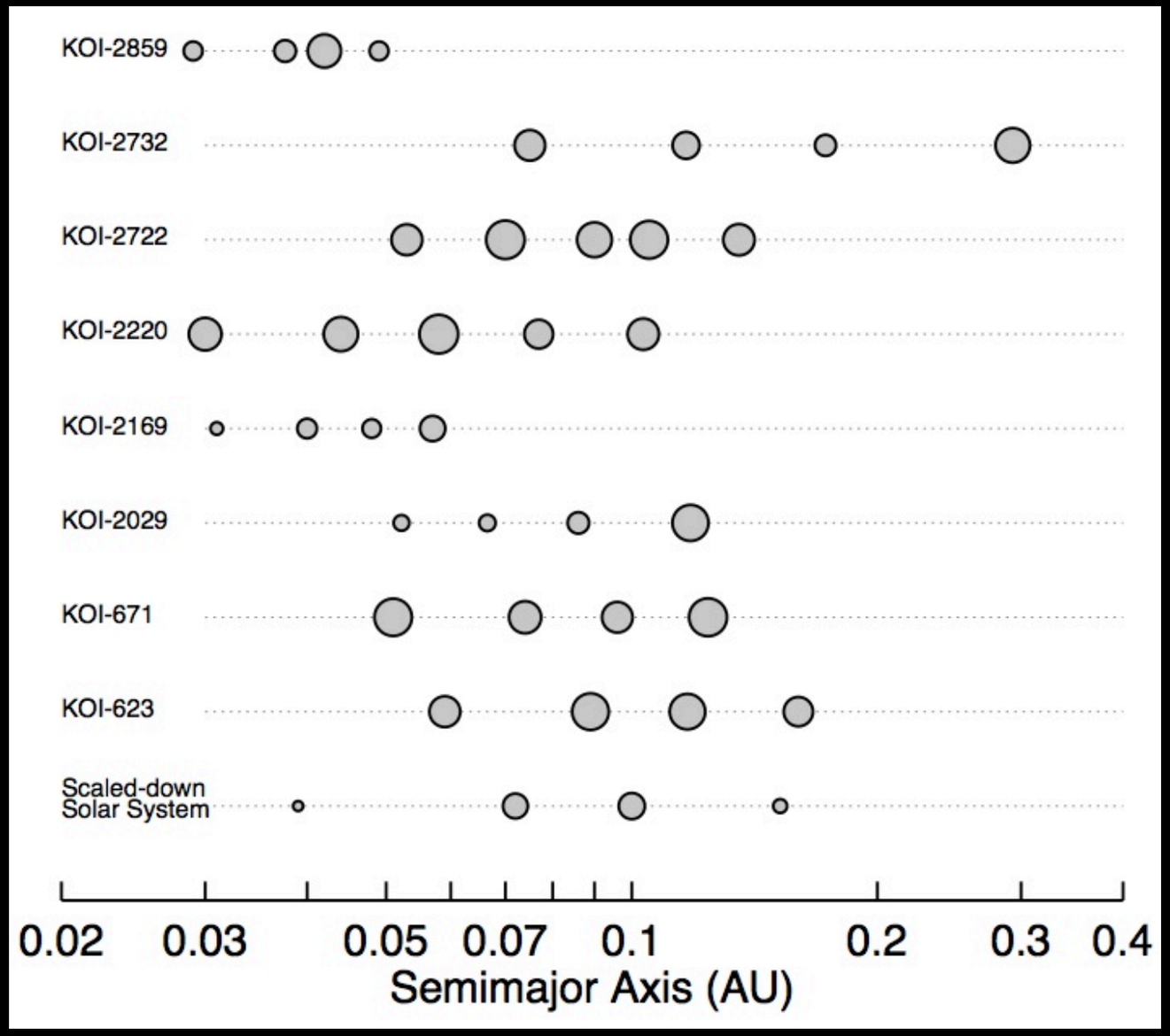


Abroad

Terrestrial planet formation in Extra-solar Systems

I. Hot Super Earths

- Exist around 30-50% of MS stars (Mayor et al 2011; Howard et al 2010, 2012; Fressin et al 2013)
- Multiple systems (e.g., Lovis et al 2011; Lissauer et al 2011)
- Compact, non-resonant orbits (Lissauer et al 2011b)

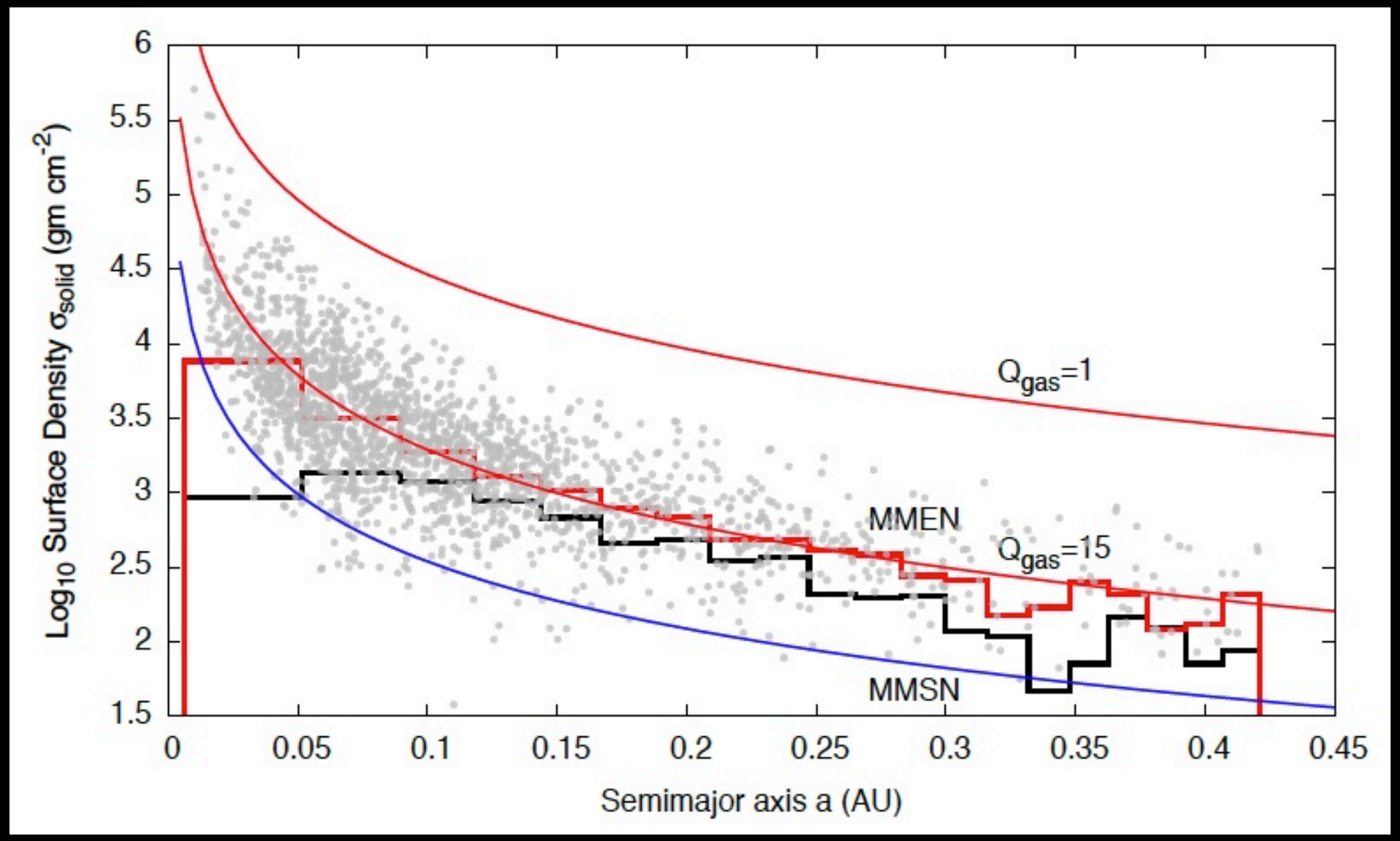


Kepler data from Batalha et al 2013, ApJS, 204, 24.

See talk by D. Fischer

A. In situ accretion

Late-stage accretion from massive inner disks (Raymond et al 2008; Hansen & Murray 2012, 2013)



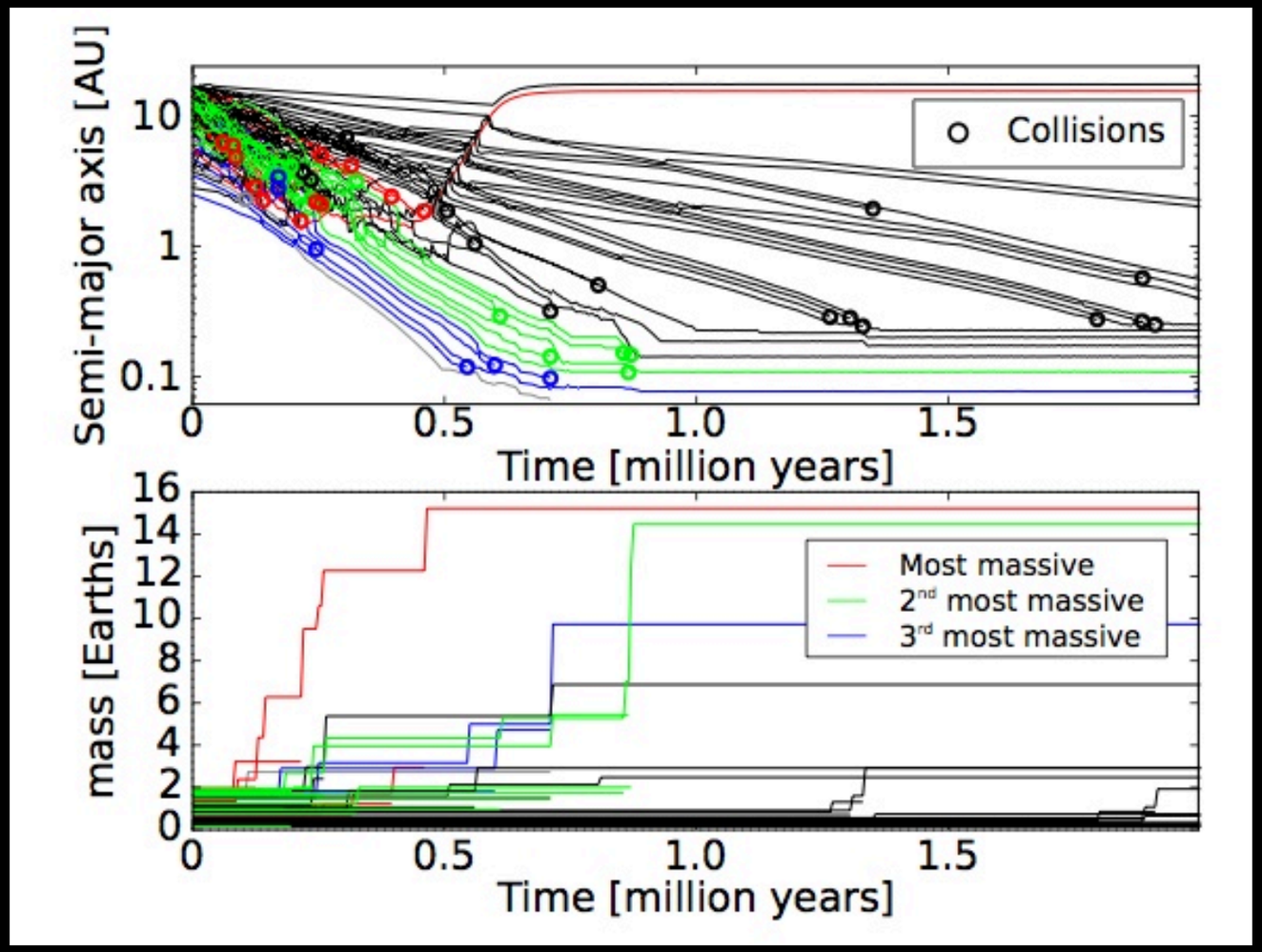
Chiang & Laughlin 2013, MNRAS, 431, 3444

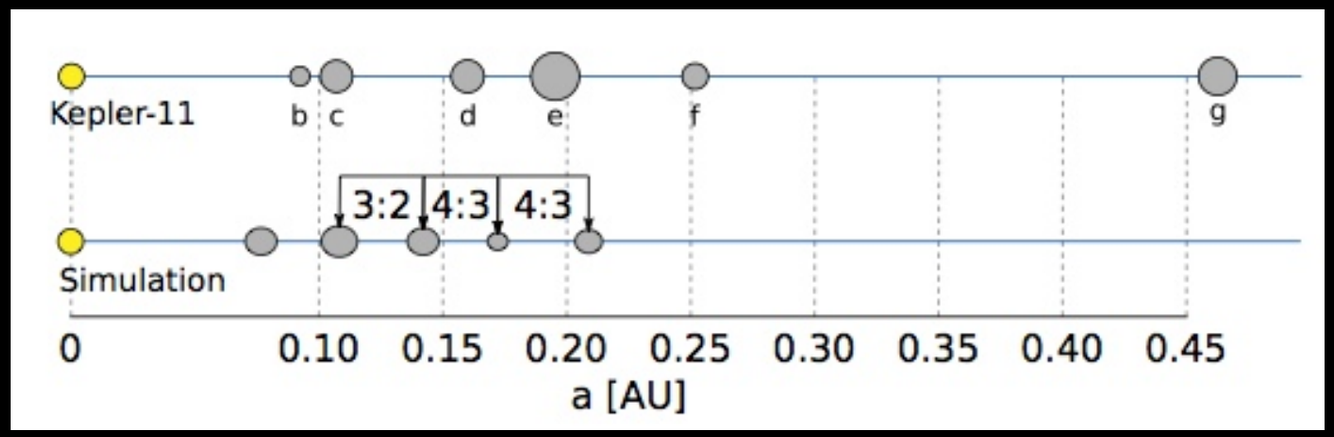
B. Type I migration

- Migration can be inwards or outwards; inwards for embryos
  (e.g., Kley & Crida 2008; Paardekooper et al 2010, 2011; Bitsch et al 2013)

- Planetary embryos migrate inward in cohorts, form planets in resonant chains
  (Terquem & Papaloizou 2007; Cresswell & Nelson 2008; Ogihara & Ida 2009)

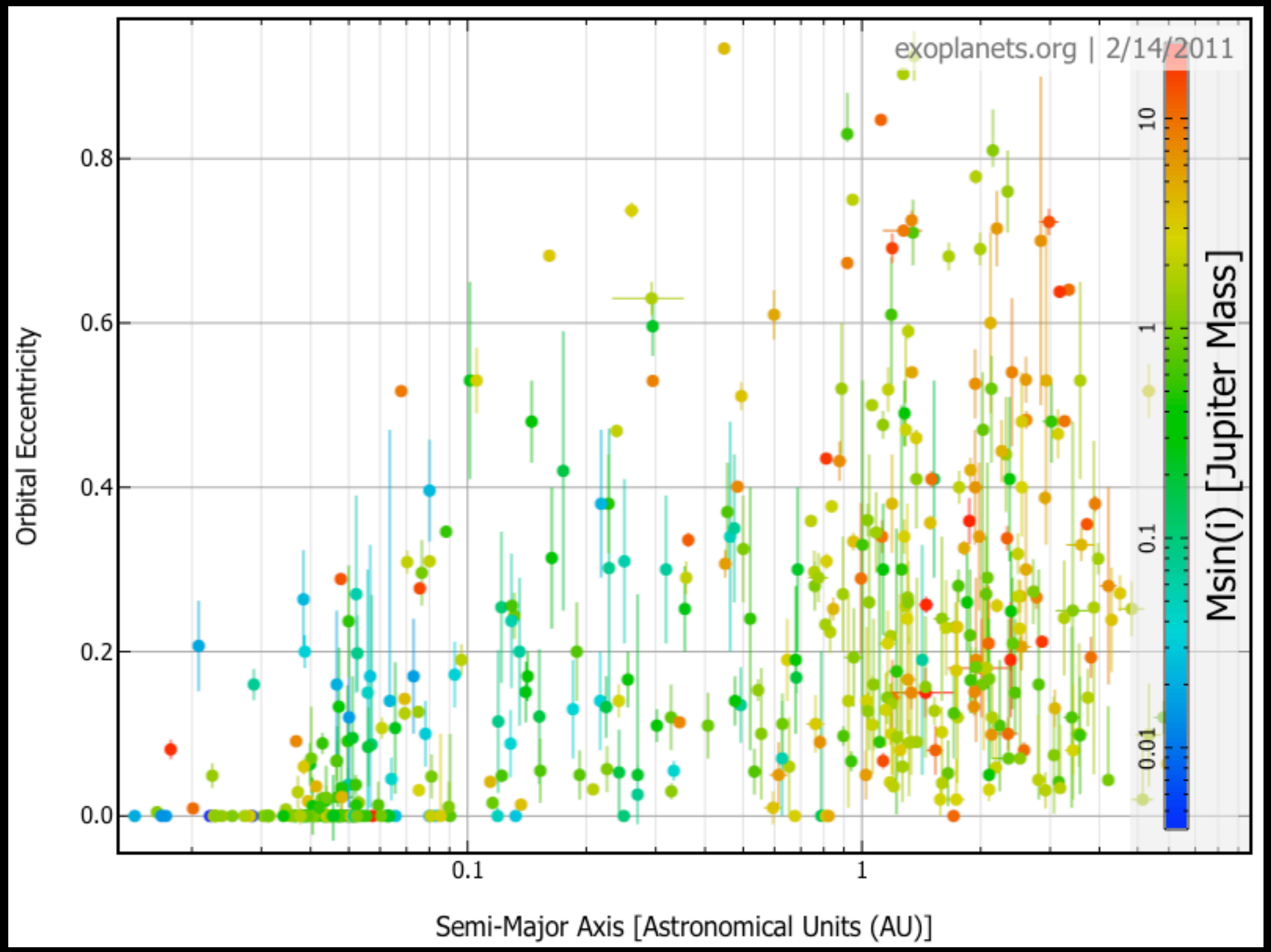
See talk by A. Crida, poster by Hands & Alexander





Cossou et al 2013, arXiv:1307.2897

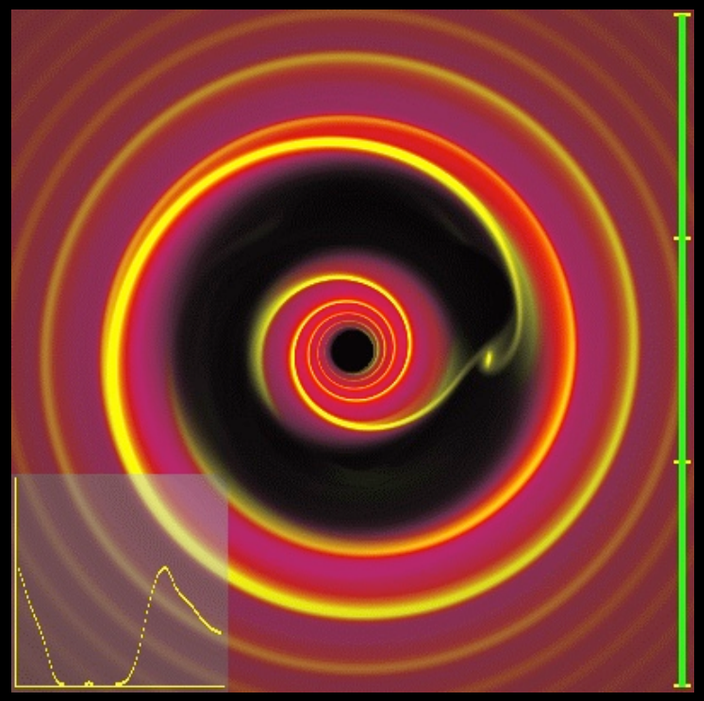
II. Giant exoplanets



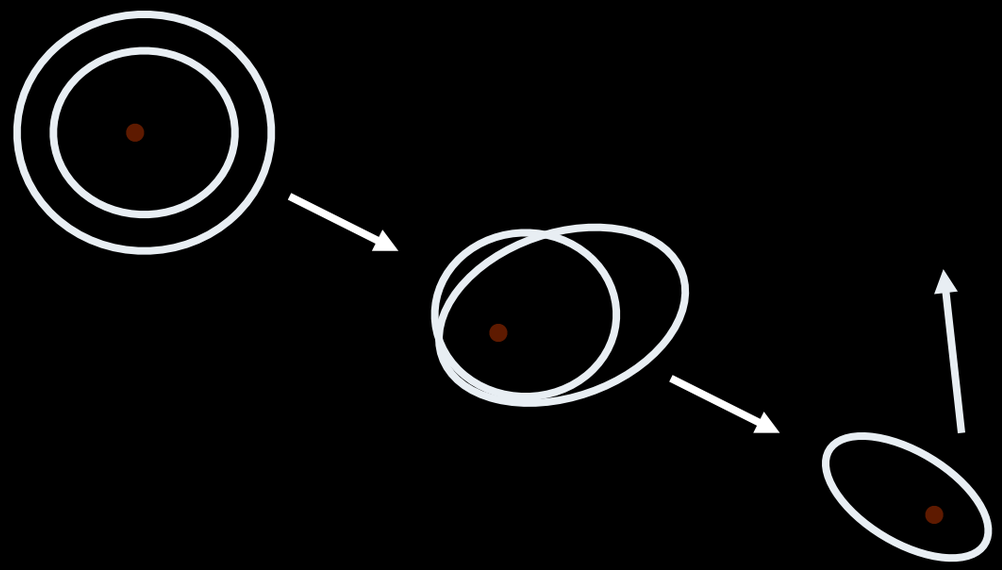
exoplanets.org; Wright et al 2011, PASP, 123, 412

II. Giant exoplanets

- Type 2 Migration (e.g., Lin et al 1996; Armitage 2007)

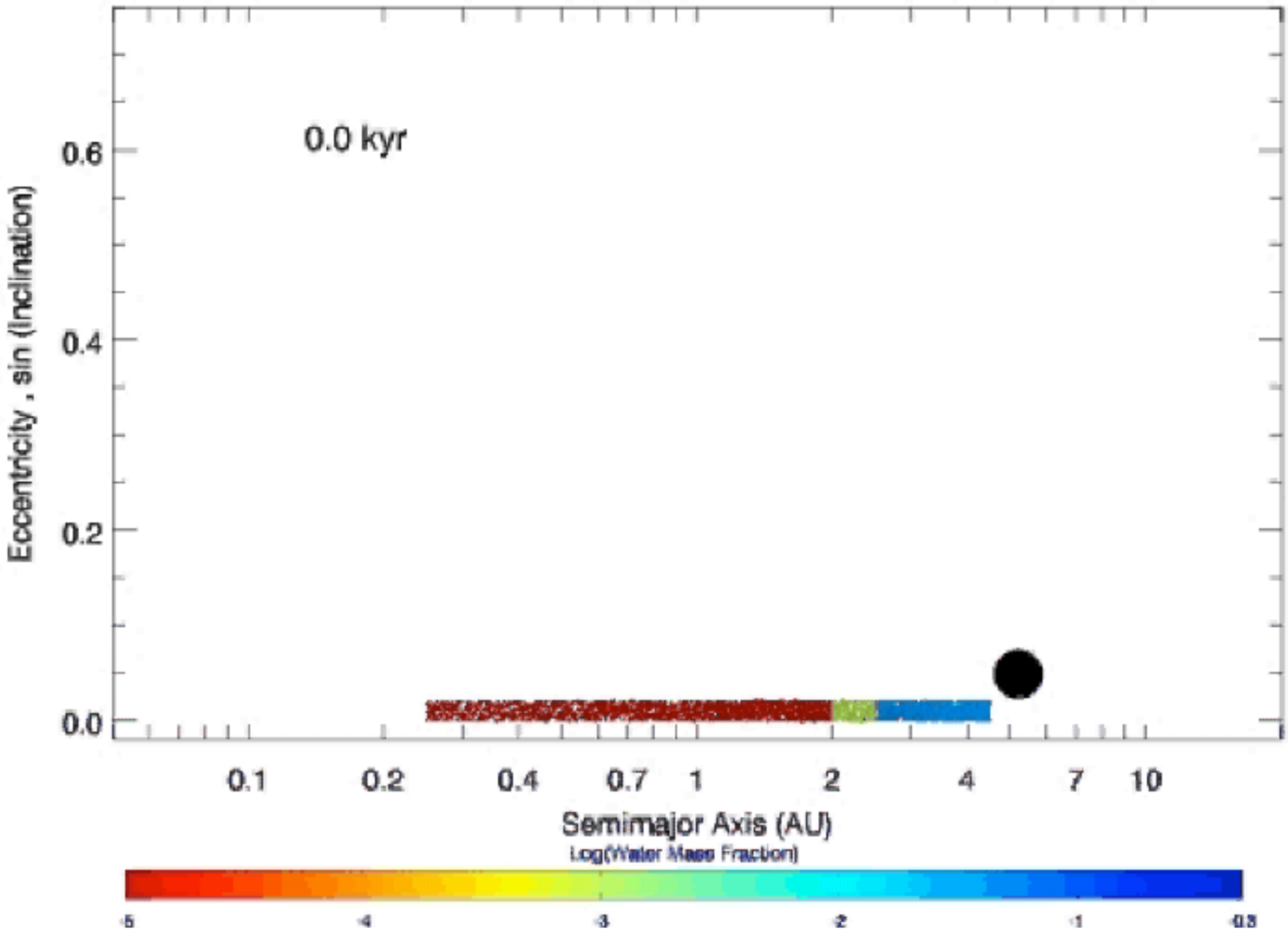


- Planet-planet scattering (e.g., Juric & Tremaine 2008; Chatterjee et al 2008)

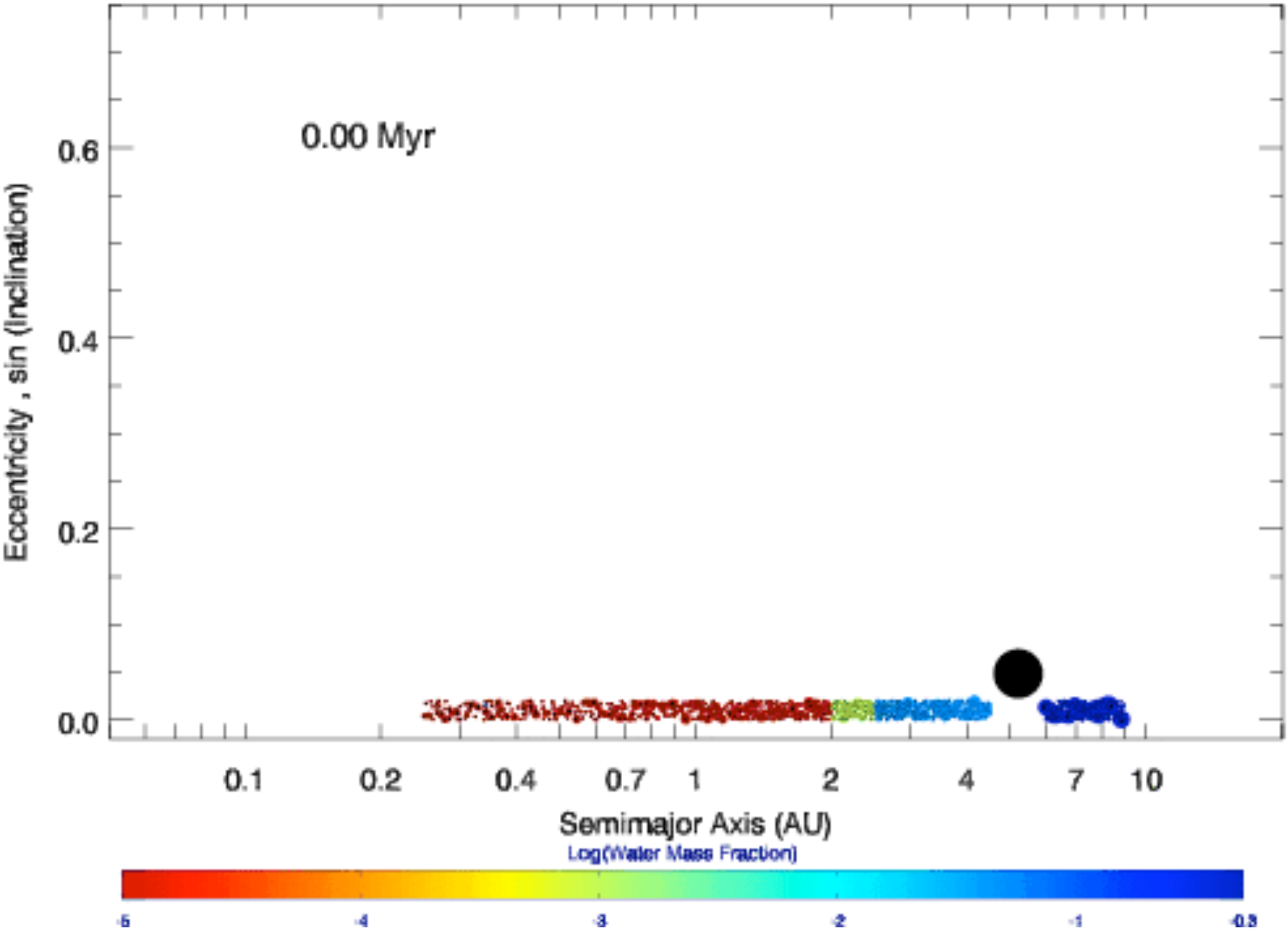


credit: Phil Armitage

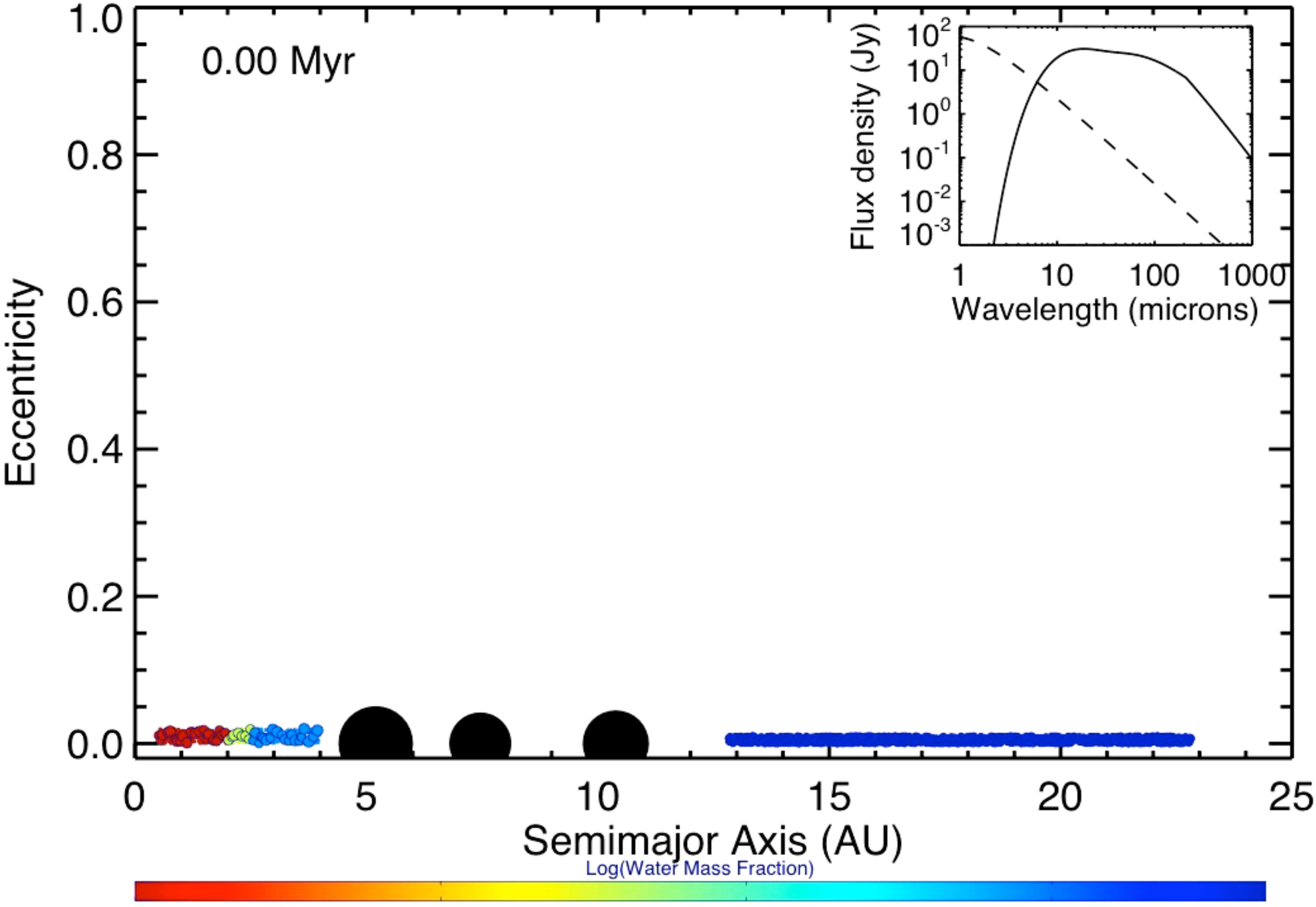
See talks by A. Crida, M. Davies



Mandell, Raymond & Sigurdsson 2007, ApJ 660, 823; see also Fogg & Nelson 2005, 2007; Zhou et al 2005



Raymond, Mandell & Sigurdsson 2006, Science, 313, 1413



Raymond et al 2012, A&A, 541, A11

At Home

Formation of the inner Solar System

Constraints

- Masses, orbits of terrestrial planets
  - Very low eccentricities
- Structure of asteroid belt
  - Separation of S, C types (Gradie & Tedesco 1982)
- Accretion timescales from Hf/W
  - Earth: 50-100 Myr (Touboul et al 2007; Kleine et al 2009)
  - Mars: few Myr (Nimmo & Kleine 2007; Dauphas & Pourmand 2011)
- Water delivery to Earth
  - Asteroidal source explains D/H (Morbidelli et al 2000, Marty & Yokochi 2006)

Stronger Constraints

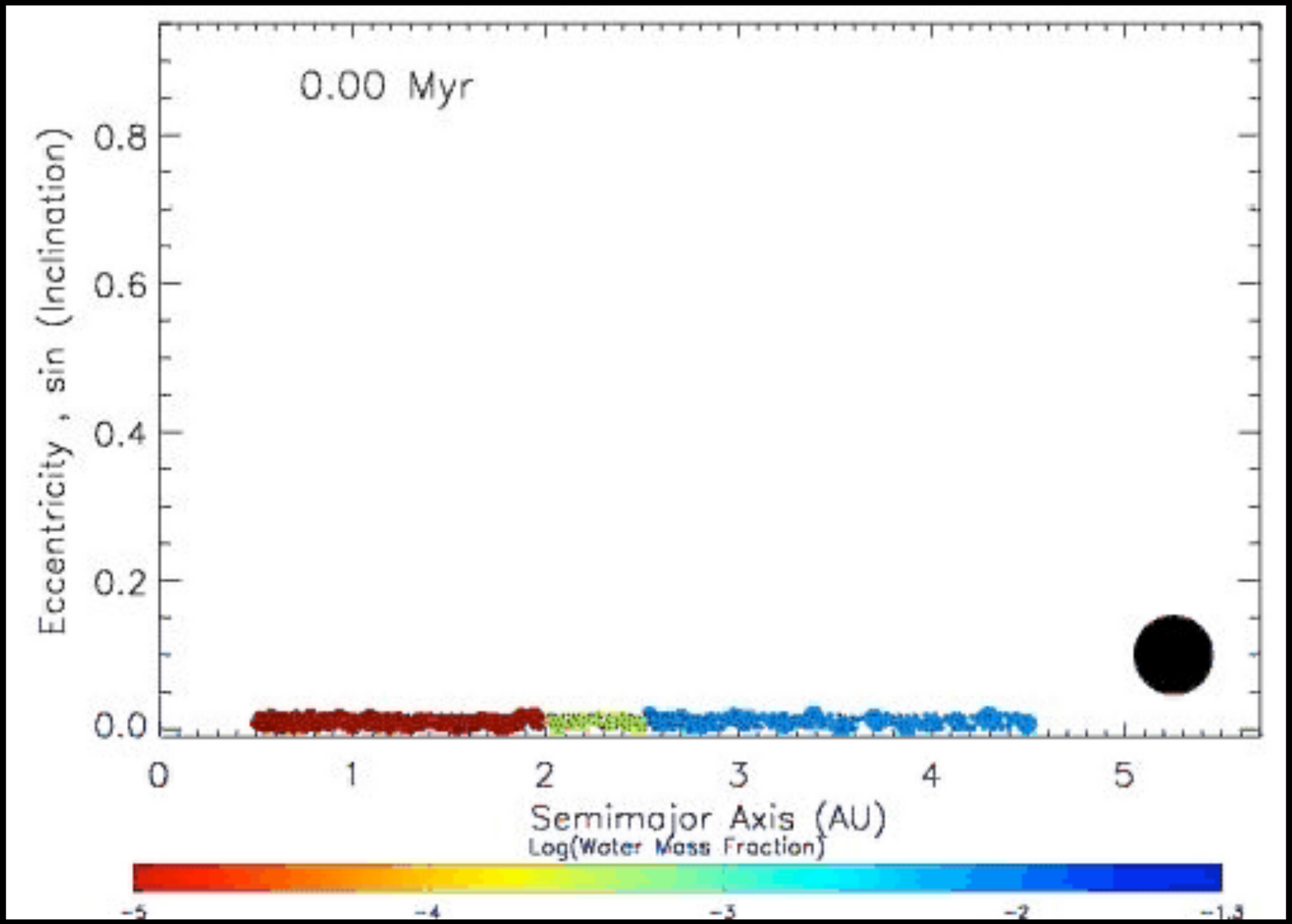
“Classical model” for terrestrial planet formation

- Jupiter, Saturn formed on current orbits (or close to them) and sculpted late stage terrestrial accretion

What were Jupiter and Saturn's orbits at early times?

- Nice model: Jup and Sat had lower eccentricities, in 3:2 resonance
- Current orbital radii, higher eccentricities

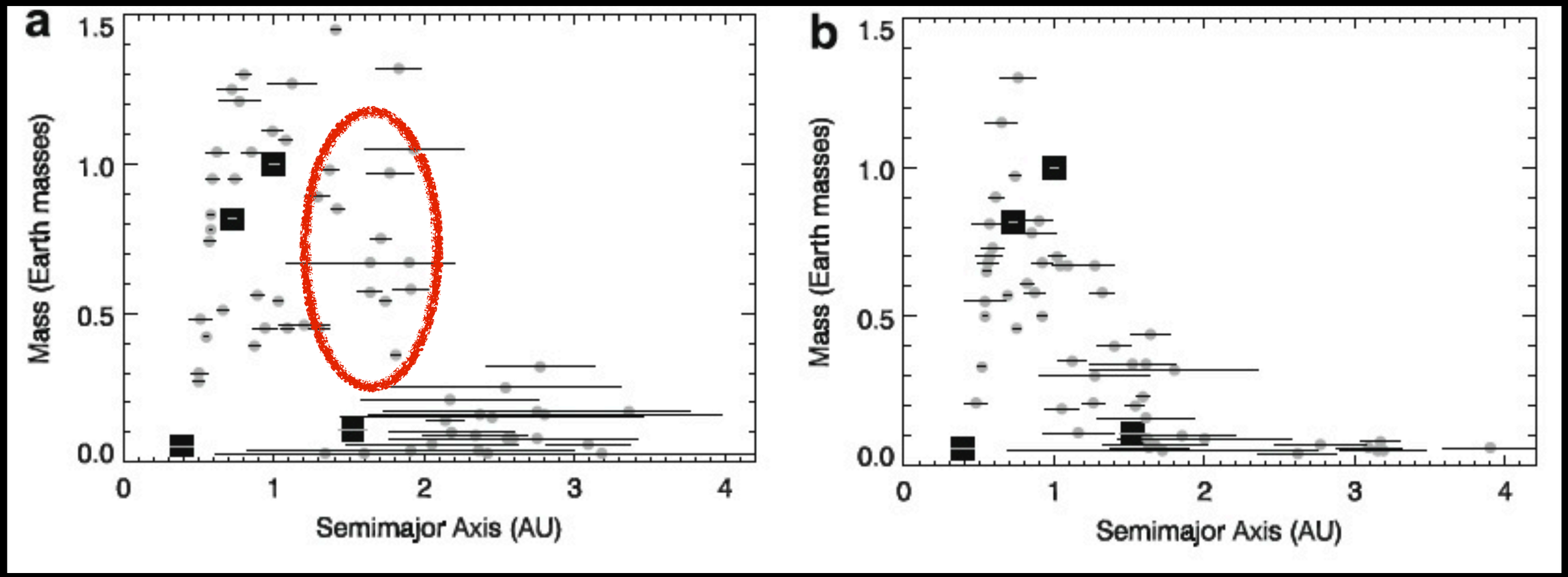
Gas giants on current orbits but with e=0.1



Raymond et al 2009, Icarus, 203, 644

Jup, Sat in resonance

$e_{Jup} \sim e_{Sat} \sim 0.1$



The Mars problem

Earth forms dry

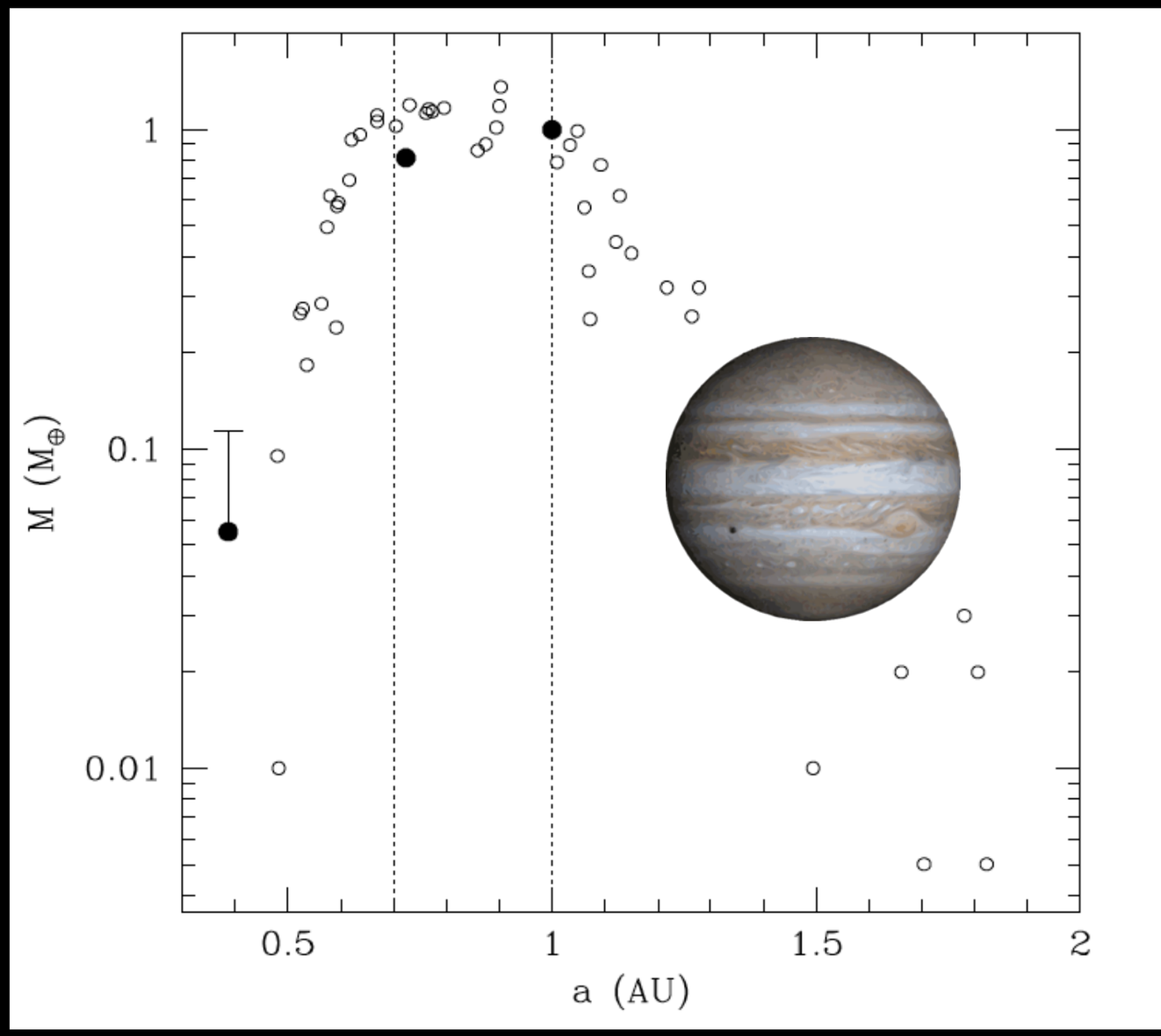
Inconsistent with late migration of giant planets

Wetherill 1991; Chambers 2001; O'Brien et al 2006; Raymond et al 2006, 2009, Morishima et al 2008, 2010; Nagasawa et al 2005, 2007; Thommes et al 2008

A possible solution to the Mars problem

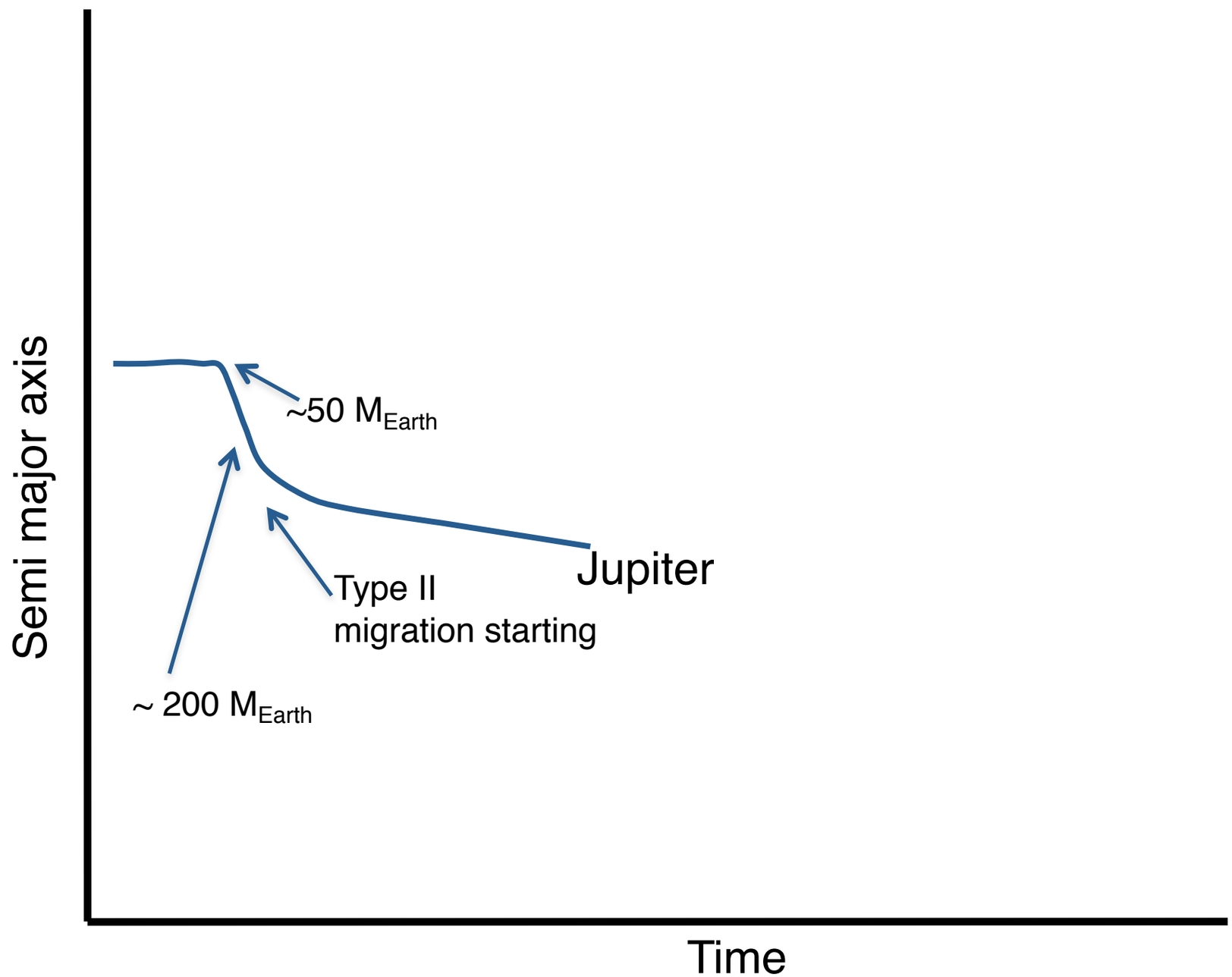
(Hansen 2009; also Wetherill 1978; Chambers 2001)

- A small Mars forms naturally if inner disk is only from 0.7-1 AU
  - An edge effect



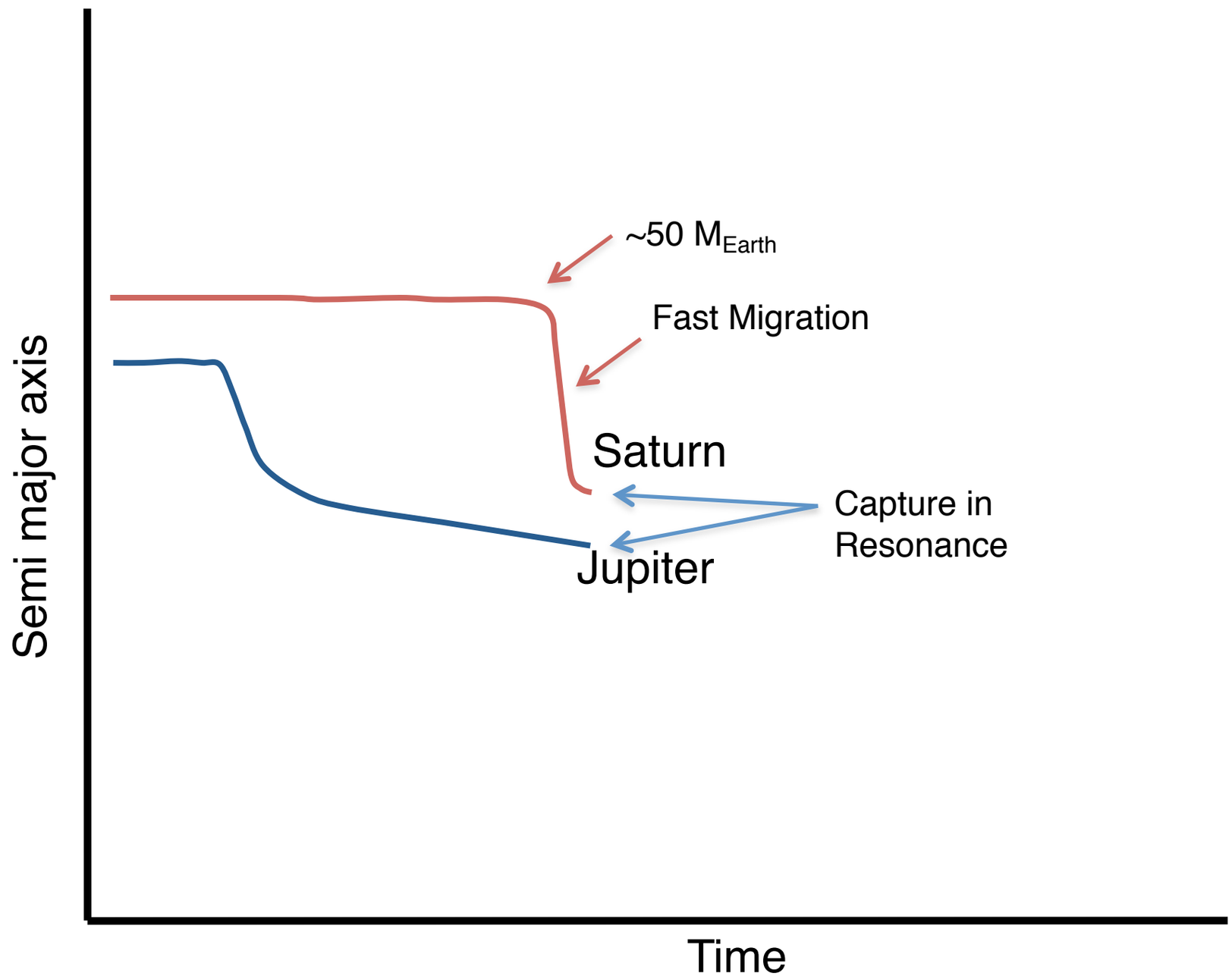
Hansen 2009, ApJ, 703, 1131

Jupiter in the gaseous disk



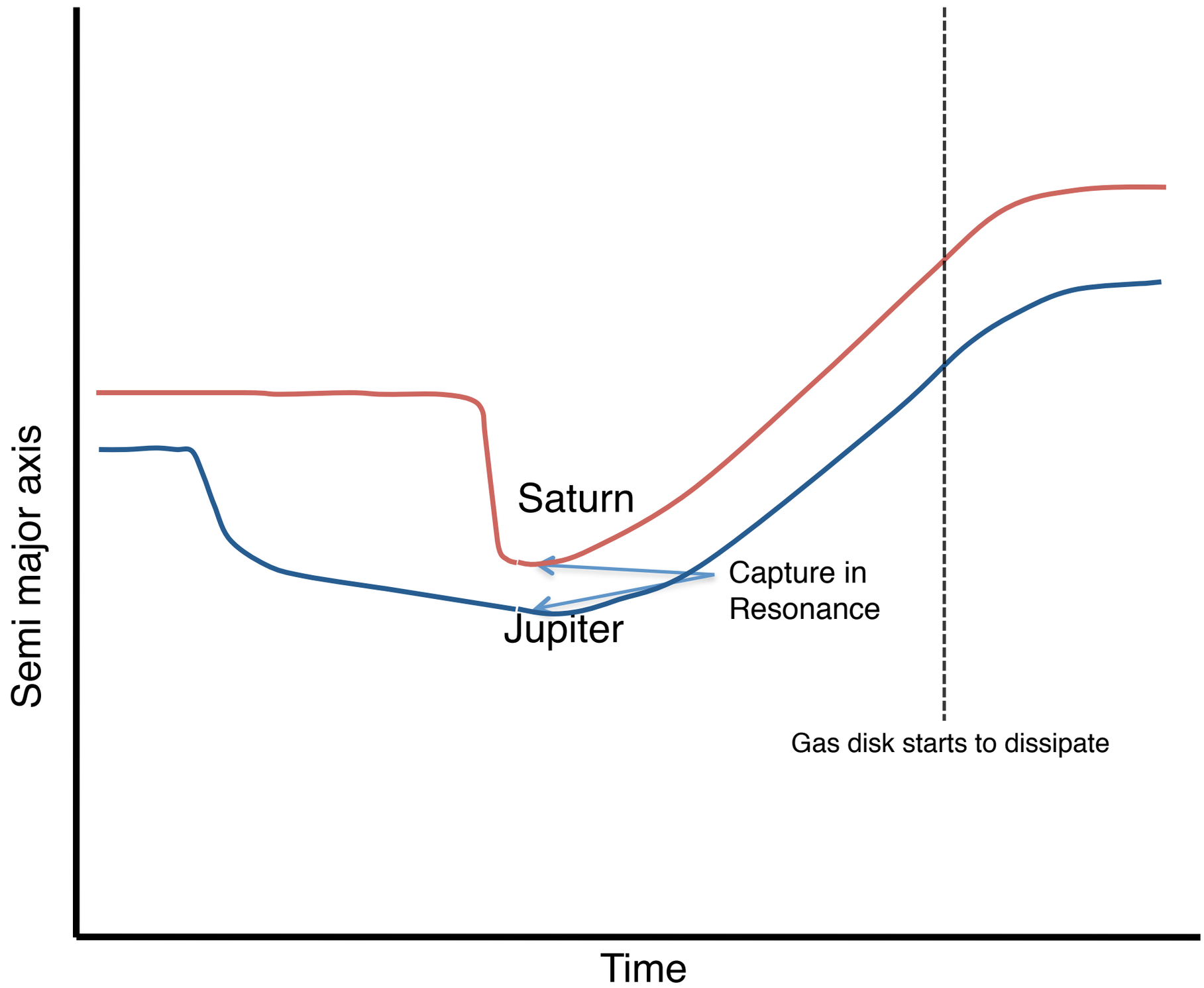
slide by Kevin Walsh

Jupiter and Saturn in the gaseous disk



slide by Kevin Walsh

Jupiter and Saturn in the gaseous disk

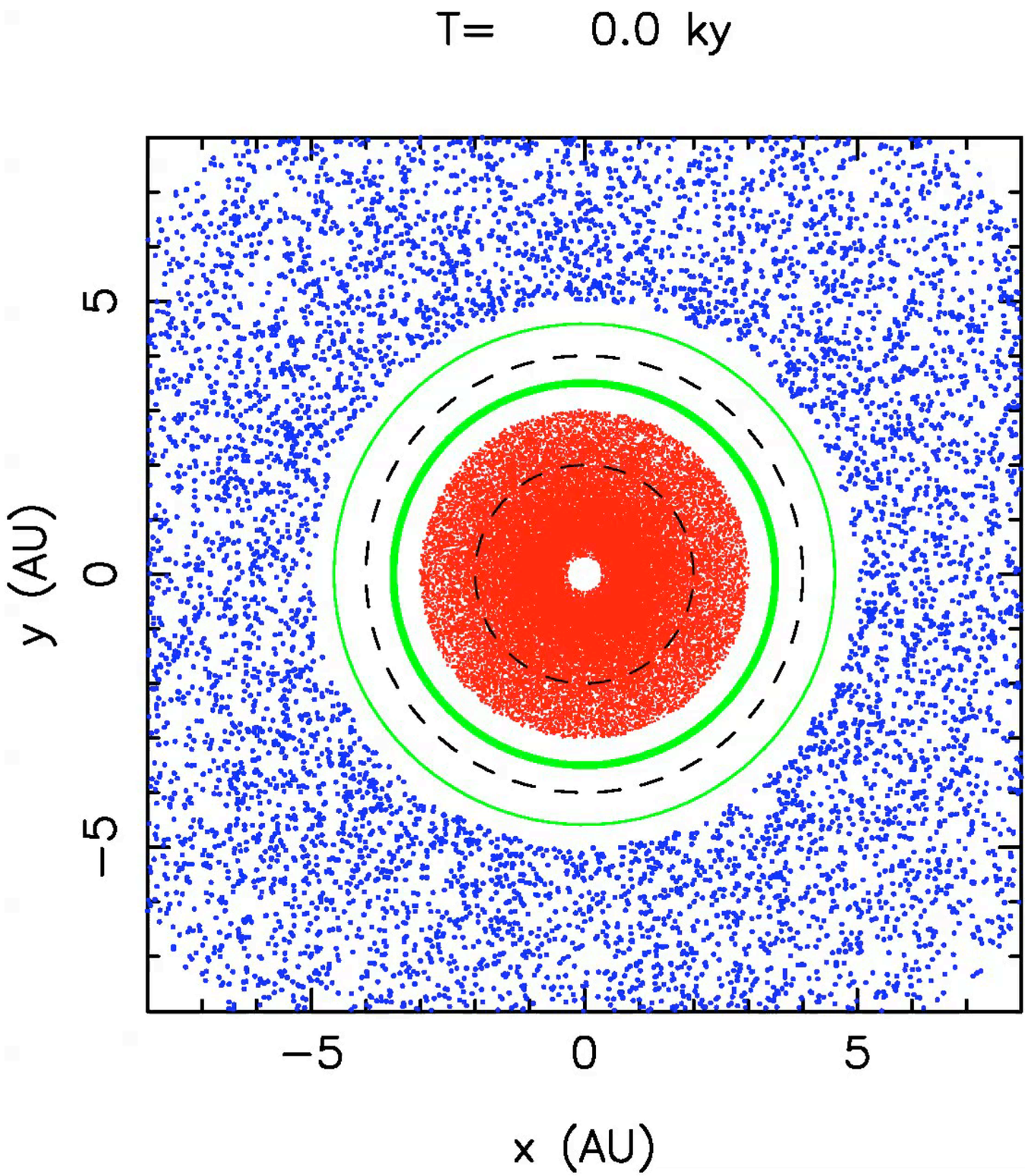


See talk by
A. Crida

Masset & Snellgrove 2001;
Morbidelli & Crida 2007;
Pierens & Nelson 2008;
Pierens & Raymond 2011

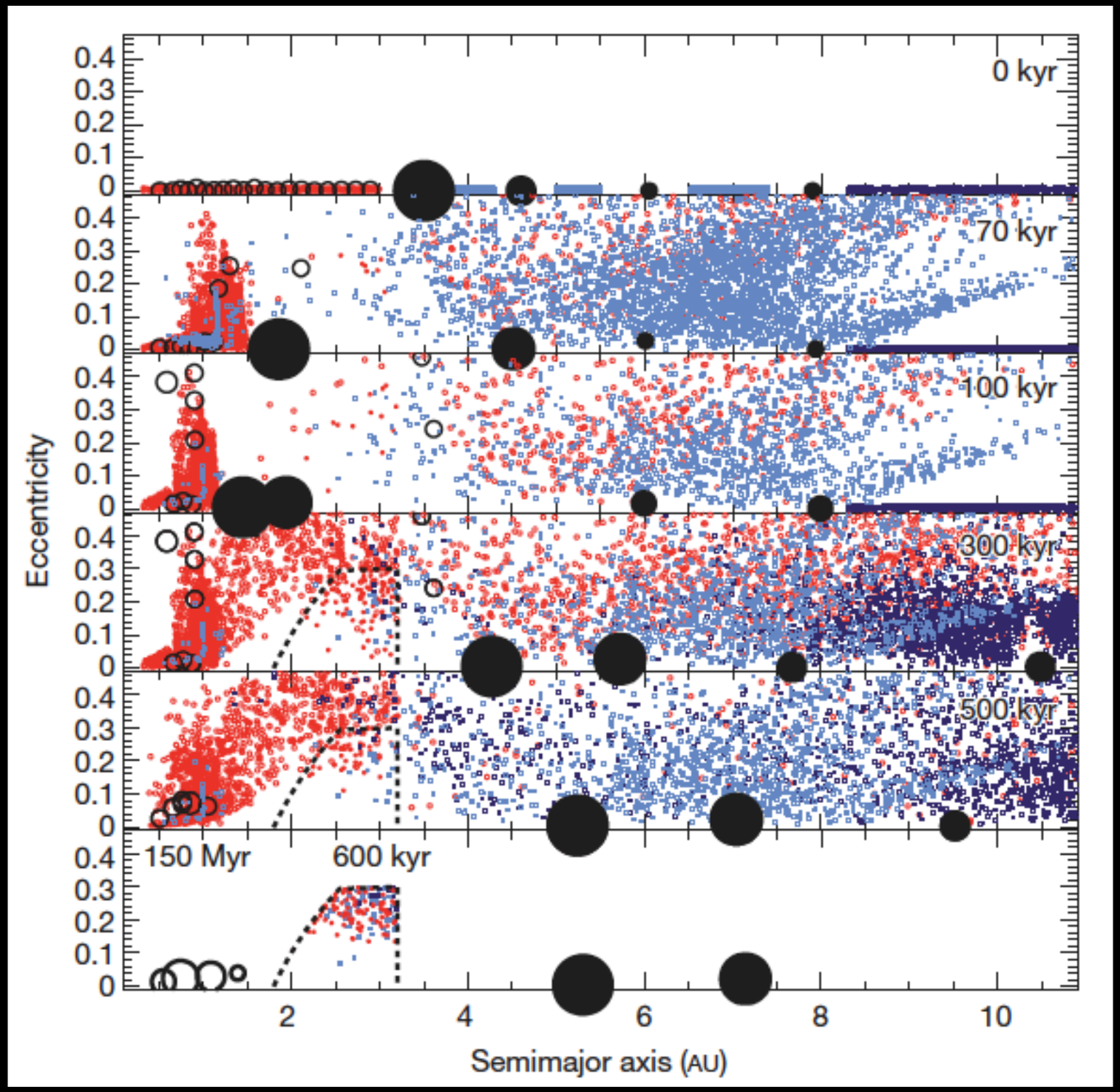
slide by Kevin Walsh

The “Grand Tack” model

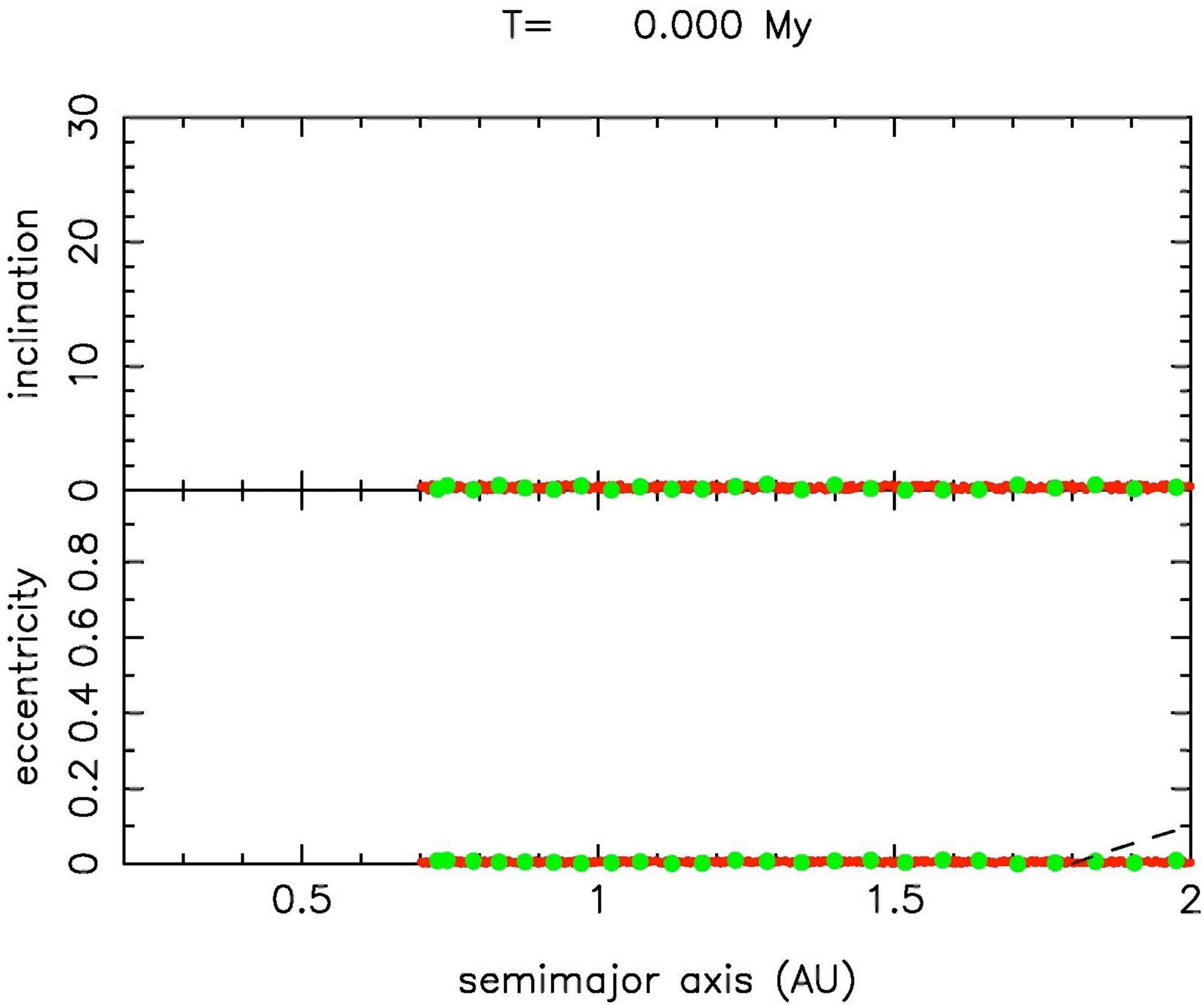


Walsh, Morbidelli, Raymond, O’Brien, Mandell 2011, Nature, 475, 206

The Grand Tack



Walsh et al 2011, Nature, 475, 206


T= 0.000 My
inclination
30
20
10
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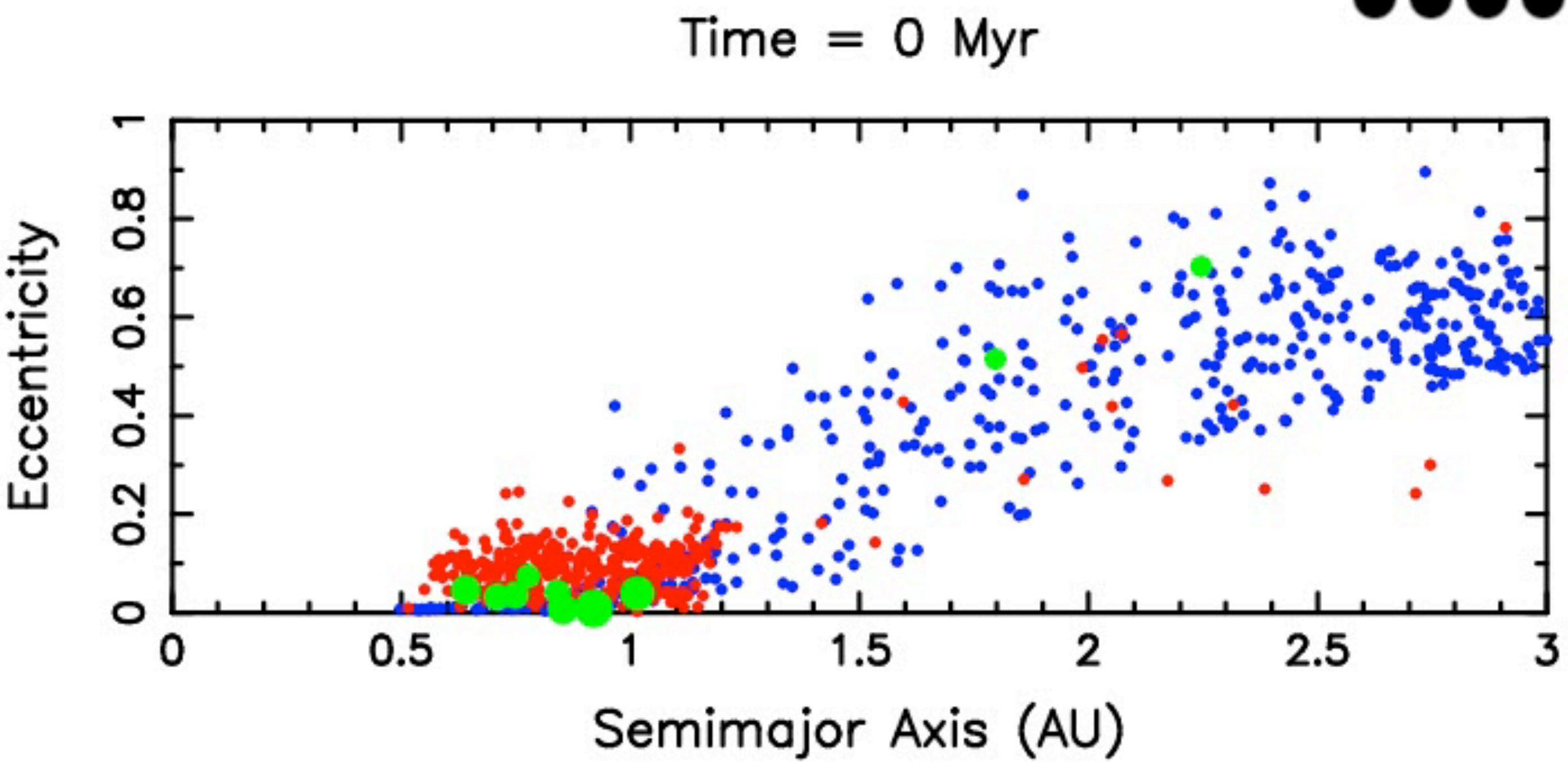
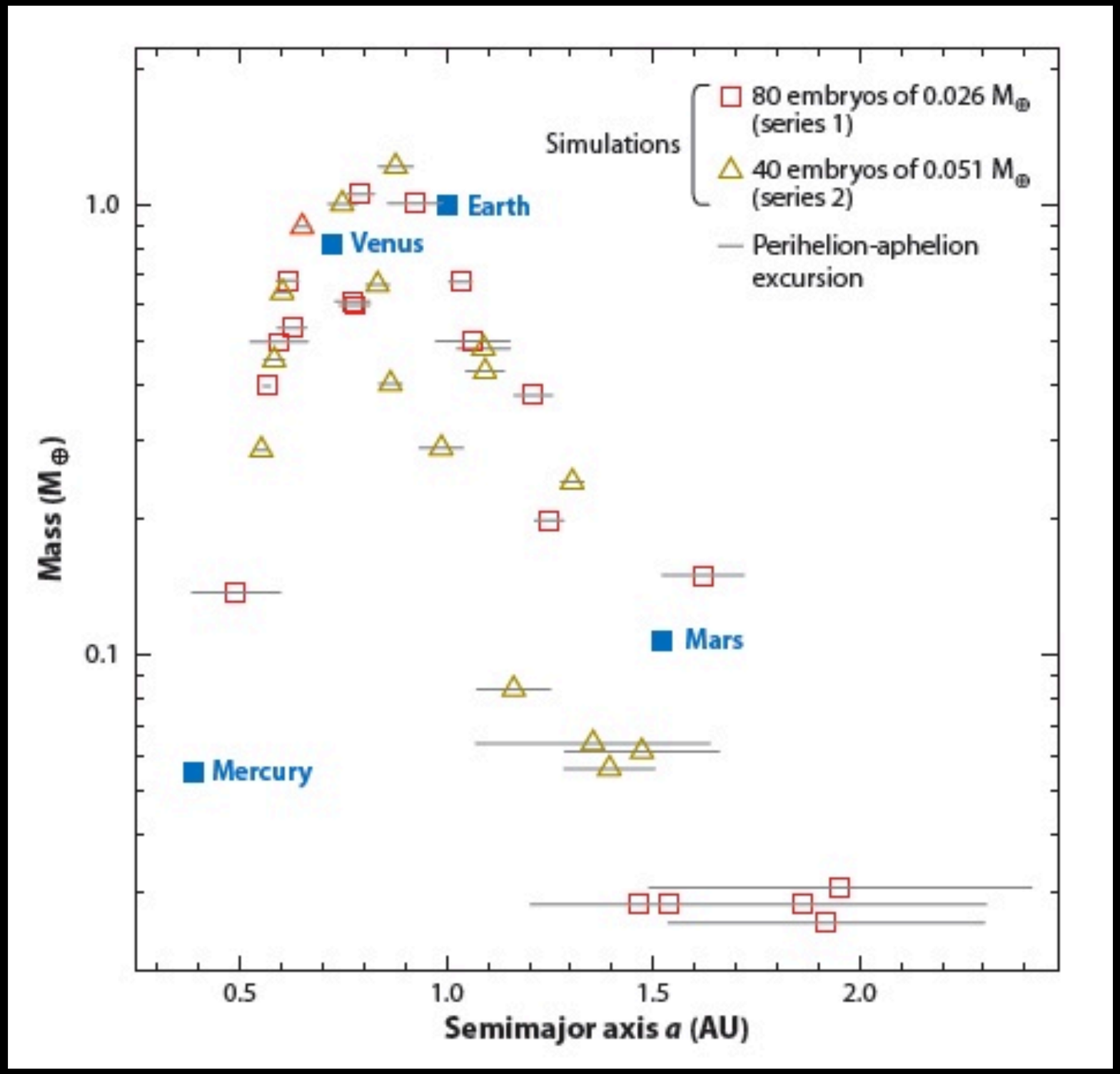
eccentricity
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
semimajor axis (AU)



Water delivered to Earth by same population that was implanted into asteroid belt as C types (O'Brien et al 2013, submitted)

See poster by S. Jacobson et al.

The terrestrial planets



Walsh et al 2011, Nature, 475, 206; Morbidelli et al 2012, AREPS, 40, 251.

Summary

- Embryos from planetesimals or pebbles
- Hot Super Earths by in situ accretion or type 1 migration
- Giant exoplanets shake up terrestrial accretion
- “Classical” accretion model: Mars problem
- Grand Tack model makes a small Mars

Terrestrial planet formation at home and abroad

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Eiichiro Kokubo (NAOJ, Japan)
Alessandro Morbidelli (Obs. de Nice, France)
Ryuji Morishima (JPL, Caltech, USA)
Kevin Walsh (SwRI, Boulder, USA)

Image credit: NASA/Ames/JPL-Caltech