Terrestrial Planet Formation Models

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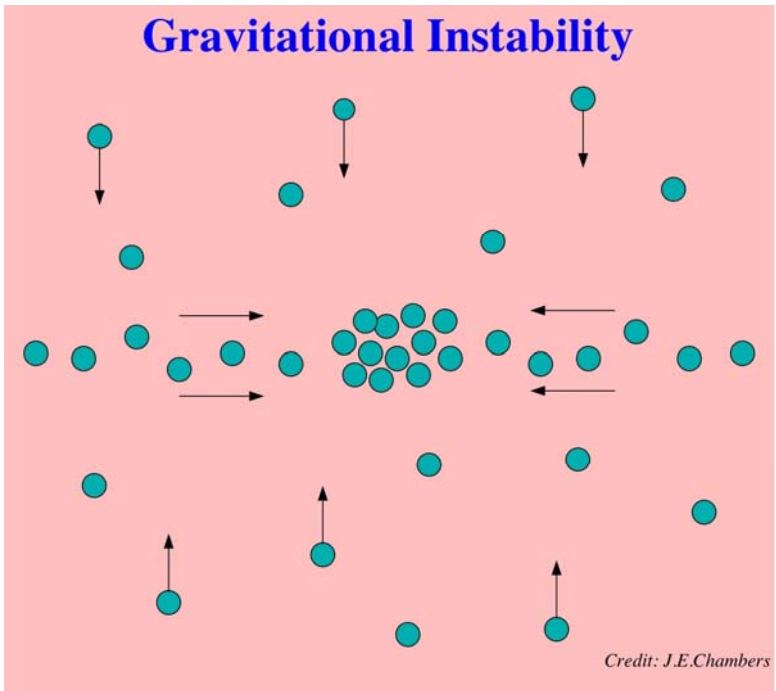
Stages of Planet Formation

1. Micron-sized dust grains coagulate into 1-1000 km planetesimals.
2. Runaway & oligarchic growth of largest planetesimals to form planetary embryos.
3. Embryos merge via giant impacts to form terrestrial planets.

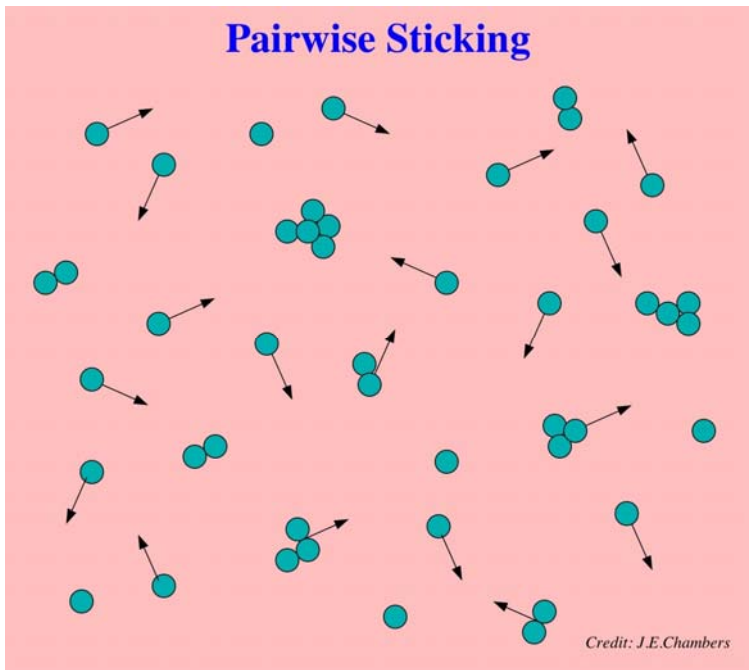
- Stellar abundances and planet formation

Planetesimal Formation

Classical Models for Planetesimal Formation

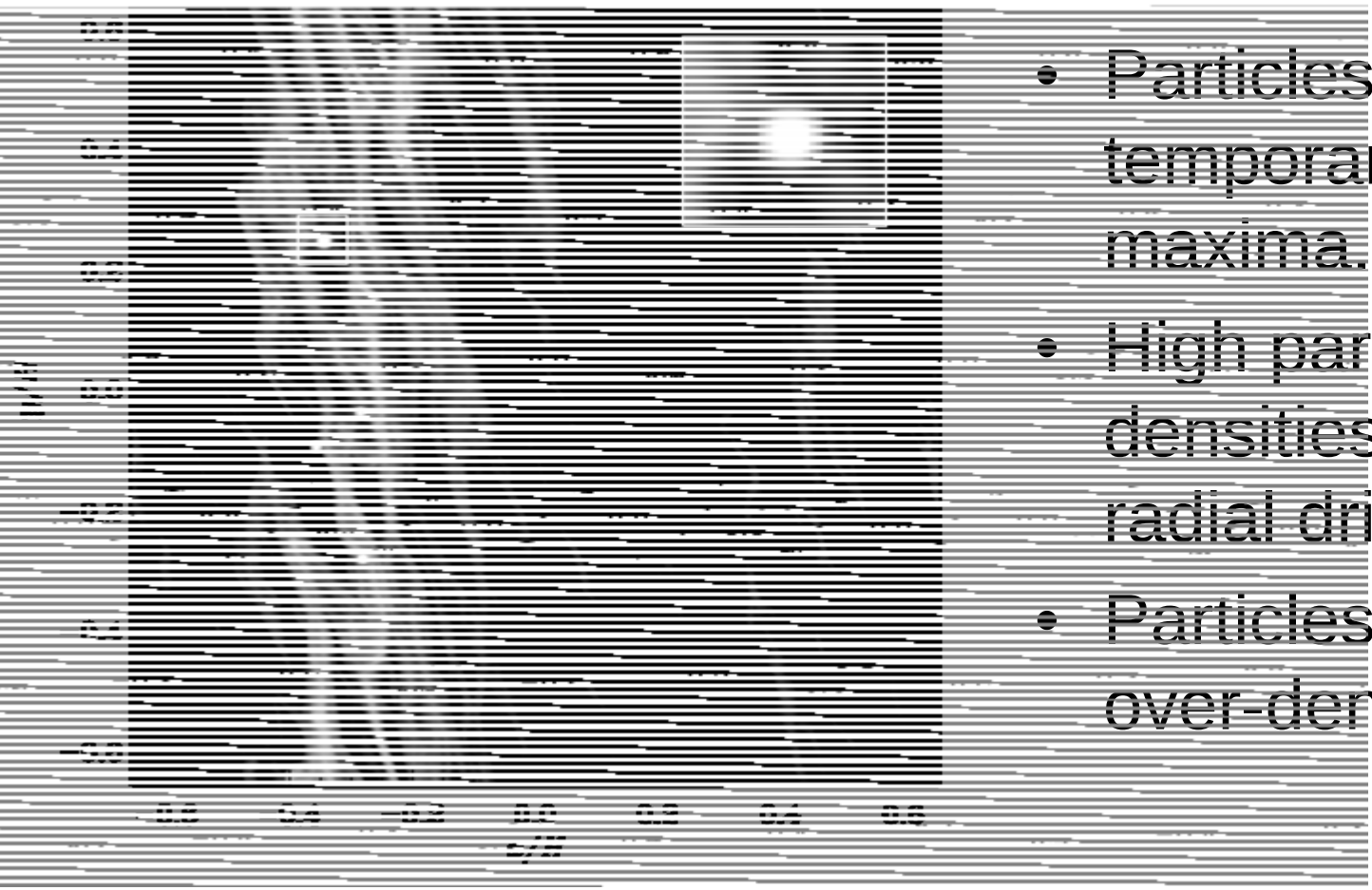


Both mechanisms are thwarted by turbulence!!



c.f. Garaud & Lin 2004
Brauer et al. 2008

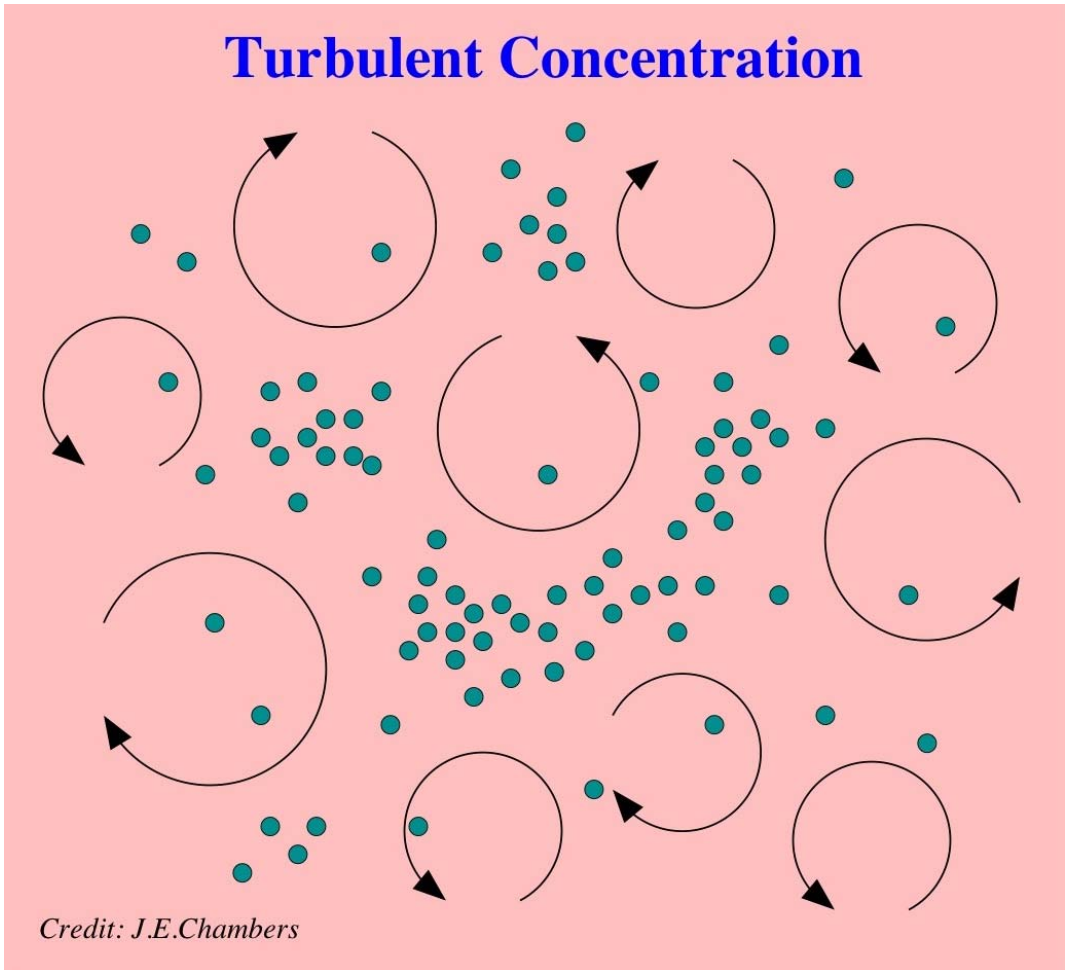
Turbulence and Streaming Instability



- Particles drift to temporary pressure maxima.
- High particle densities reduce radial drift rates.
- Particles pile up in over-dense regions.

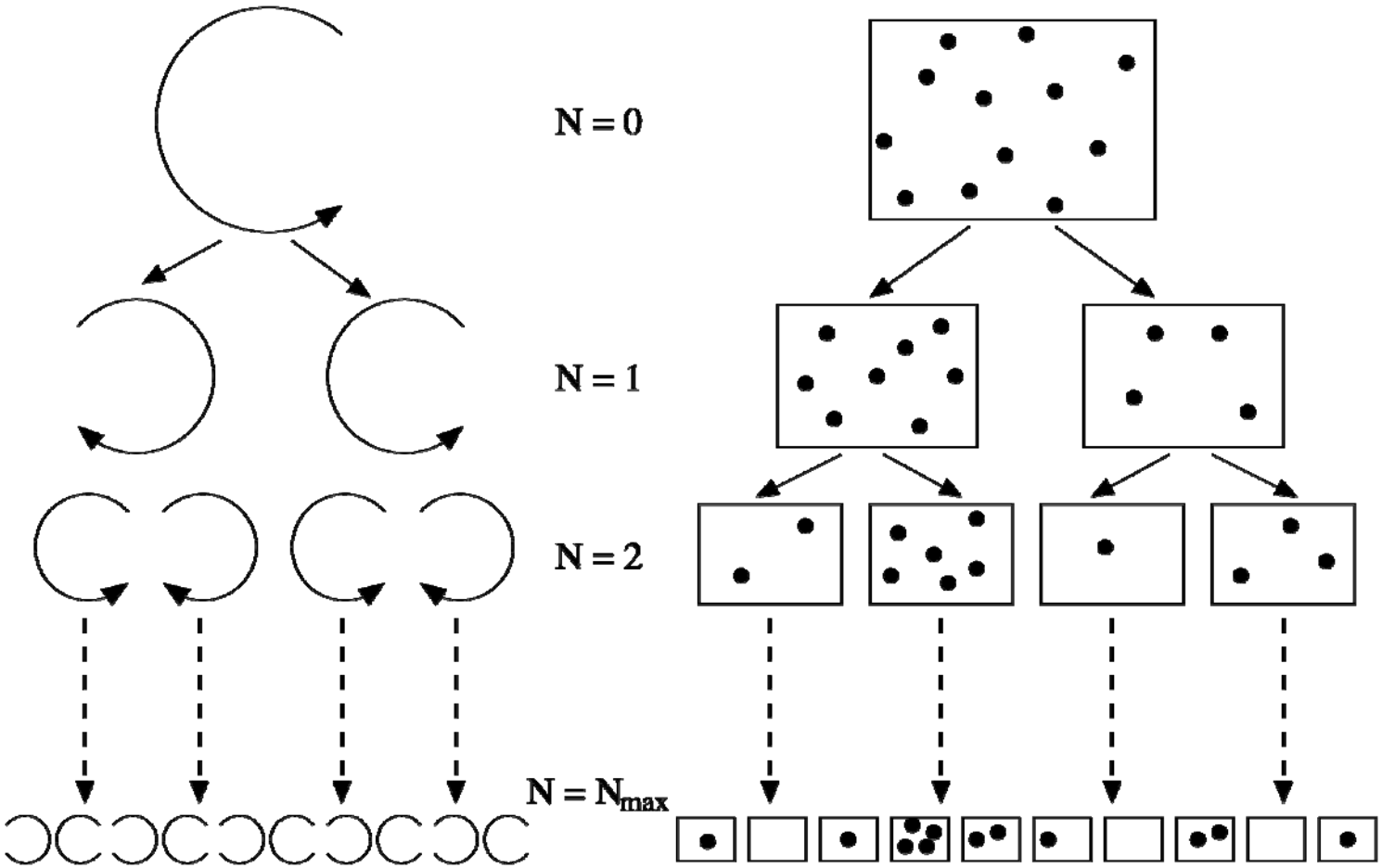
Johansen et al. 2007

Turbulent Concentration



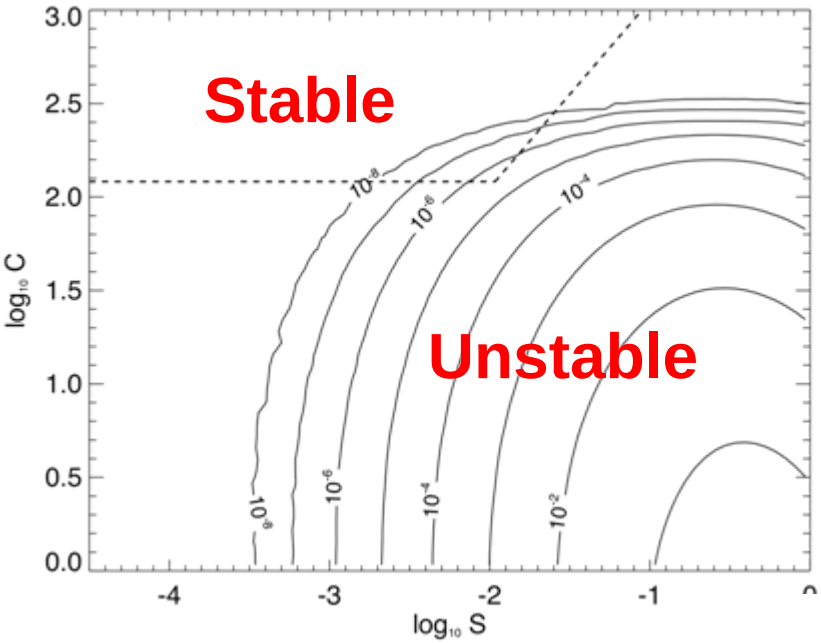
- Affects mm-size particles (i.e. chondrules).
- Inefficient: explains wide range meteorite parent-body ages.

Turbulent Cascade Model



Chambers 2010a

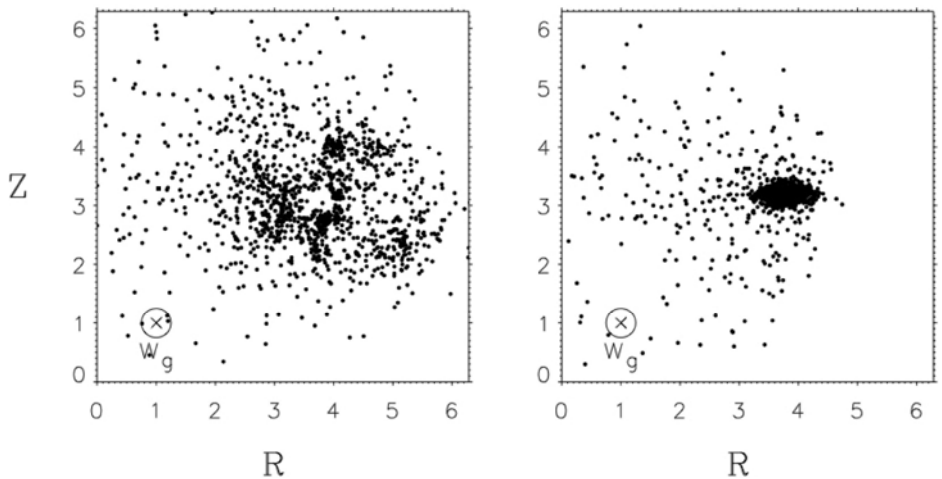
Stable Clump Formation



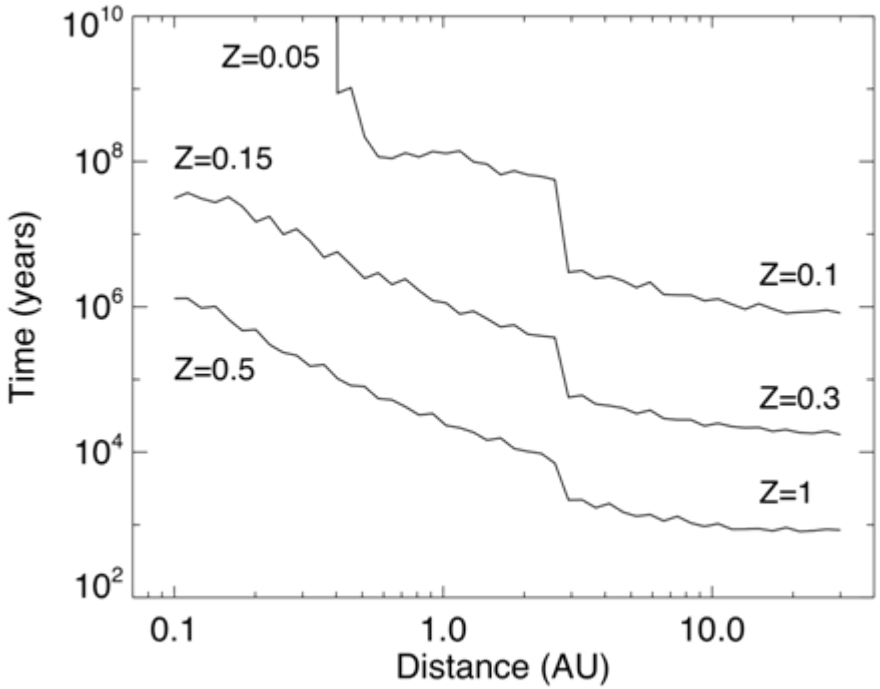
Chambers 2010a
c.f. Cuzzi et al. 2010

Cuzzi et al. 2008

No gravity **Self Gravity**

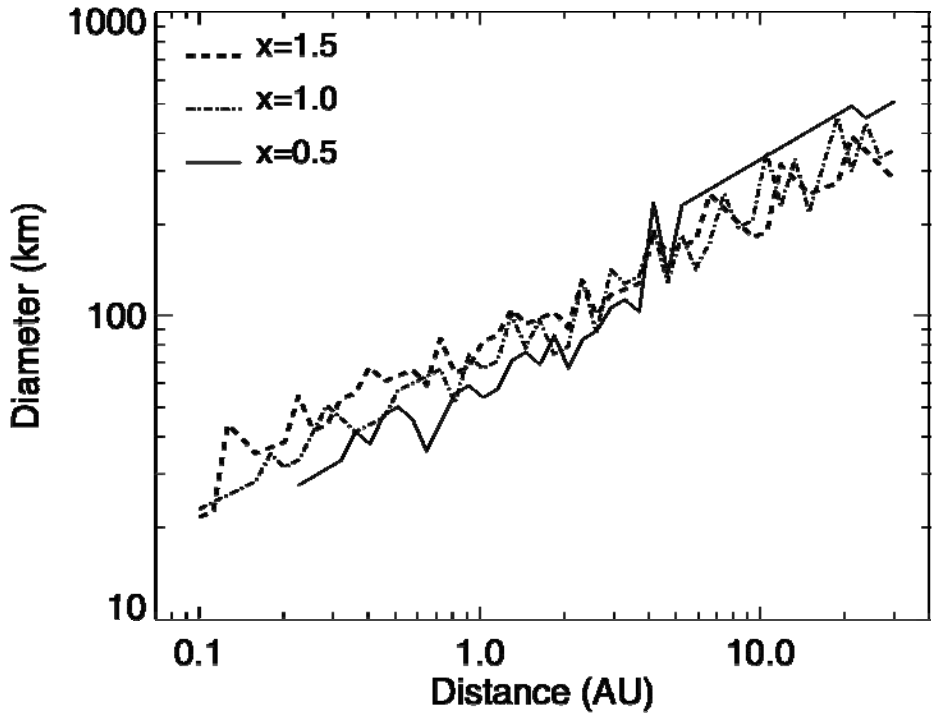


Turbulent Concentration



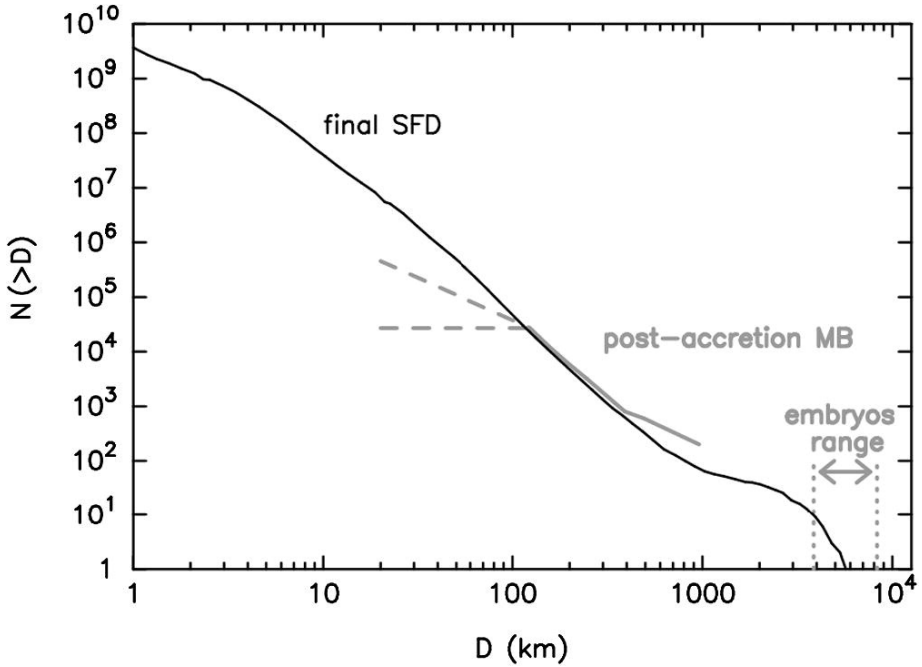
Planetesimal Formation Timescale

Modal Planetesimal Diameter



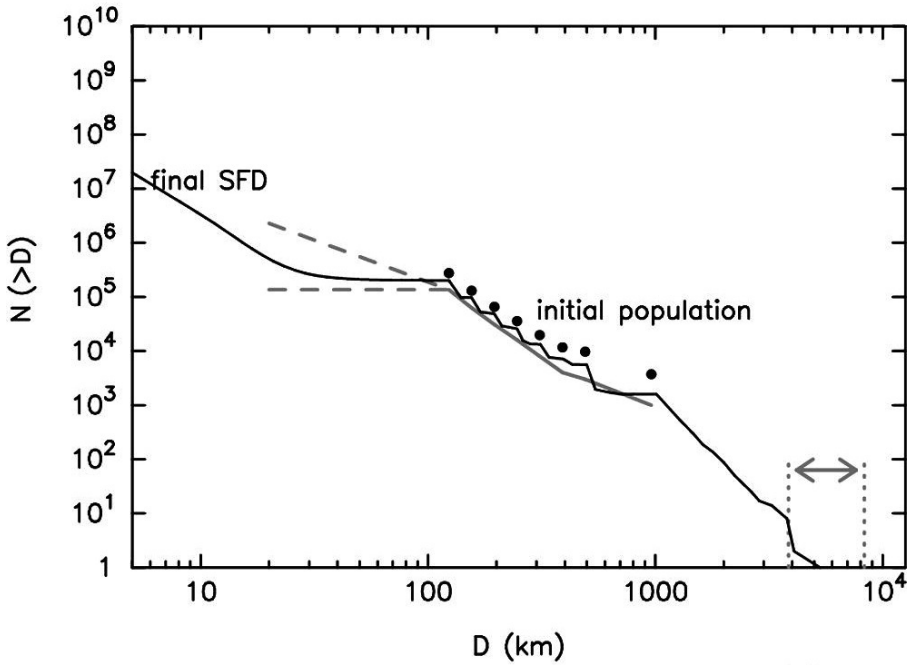
Chambers 2010a

Big Planetesimals Reproduce Asteroid Size Distribution



1 km planetesimals

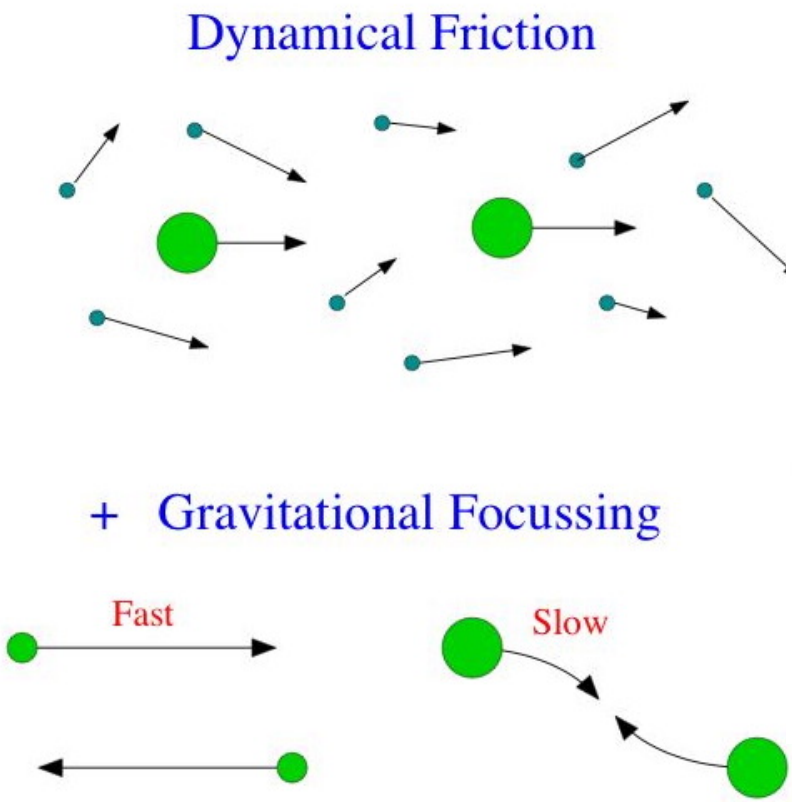
100-1000 km planetesimals

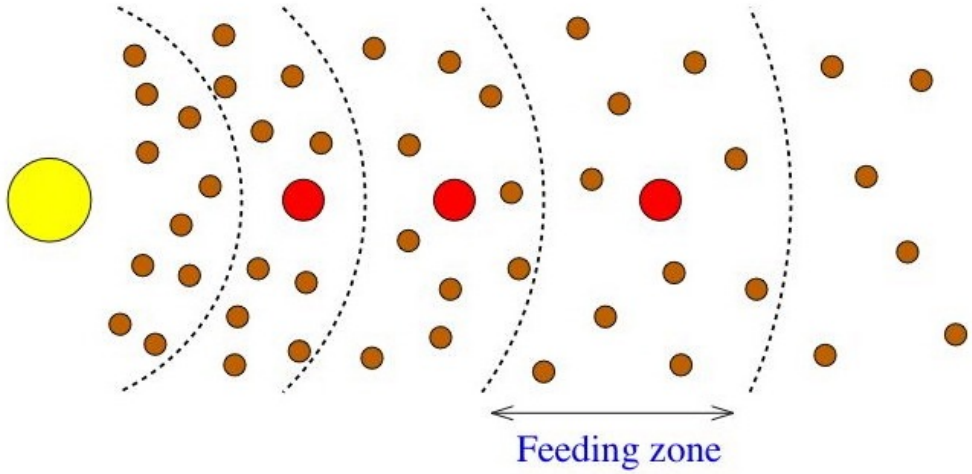


Morbidelli et al. 2009
c.f. Bottke et al. 2005

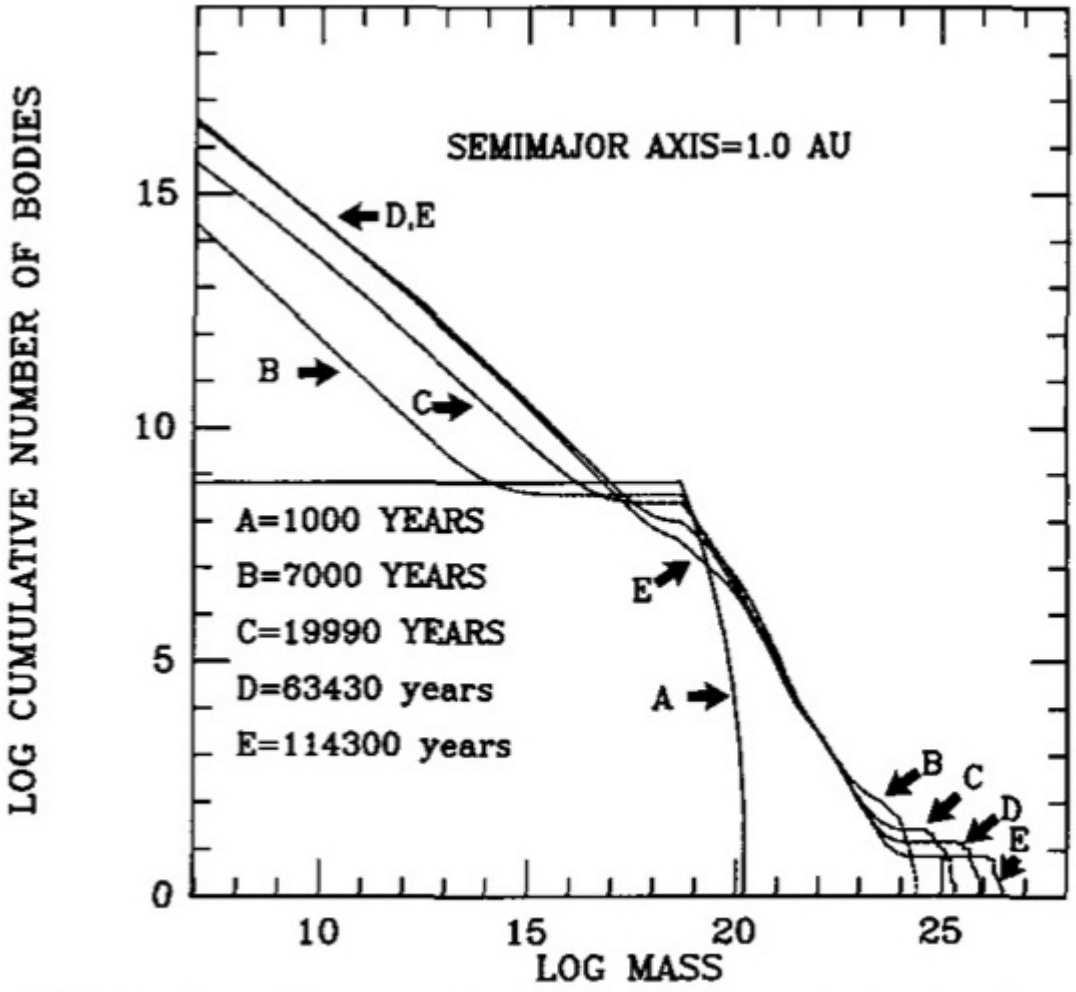
Runaway and Oligarchic Growth

Runaway and Oligarchic Growth





Runaway Growth

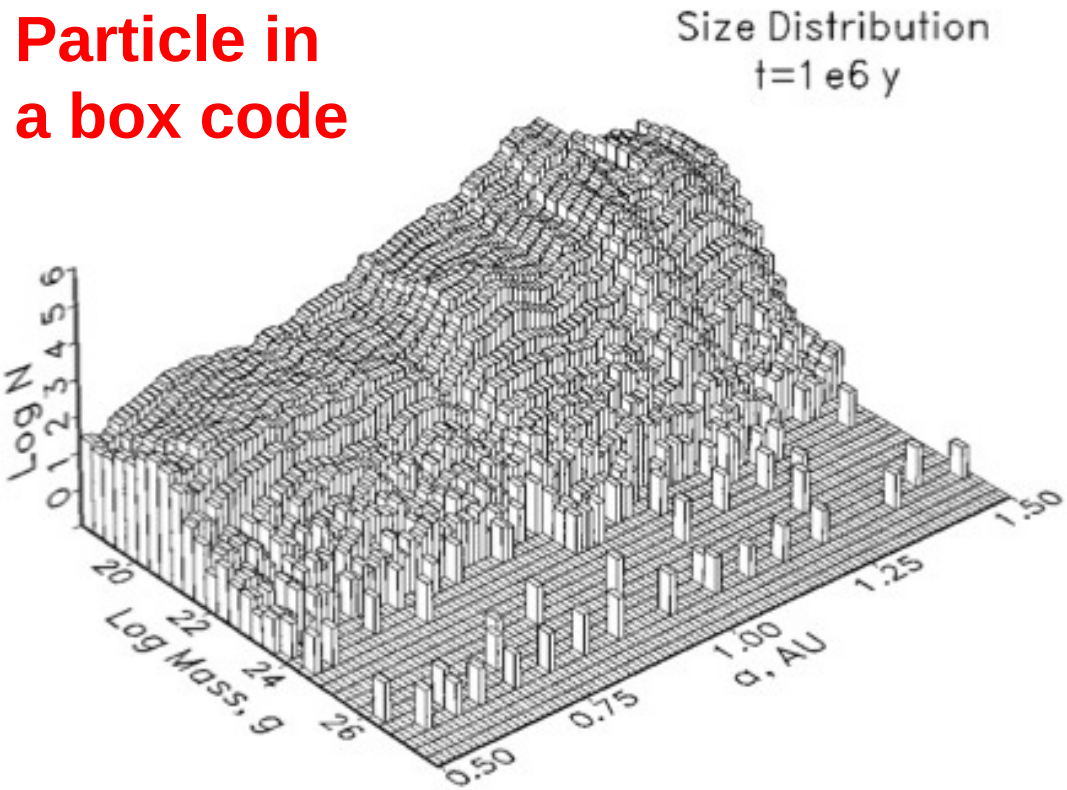


- Collisions lead to mergers and a fragmentation tail.
- Fragments swept up easily, speeding up growth.
- Discontinuity in mass distribution at largest masses.

Wetherill & Stewart 1993

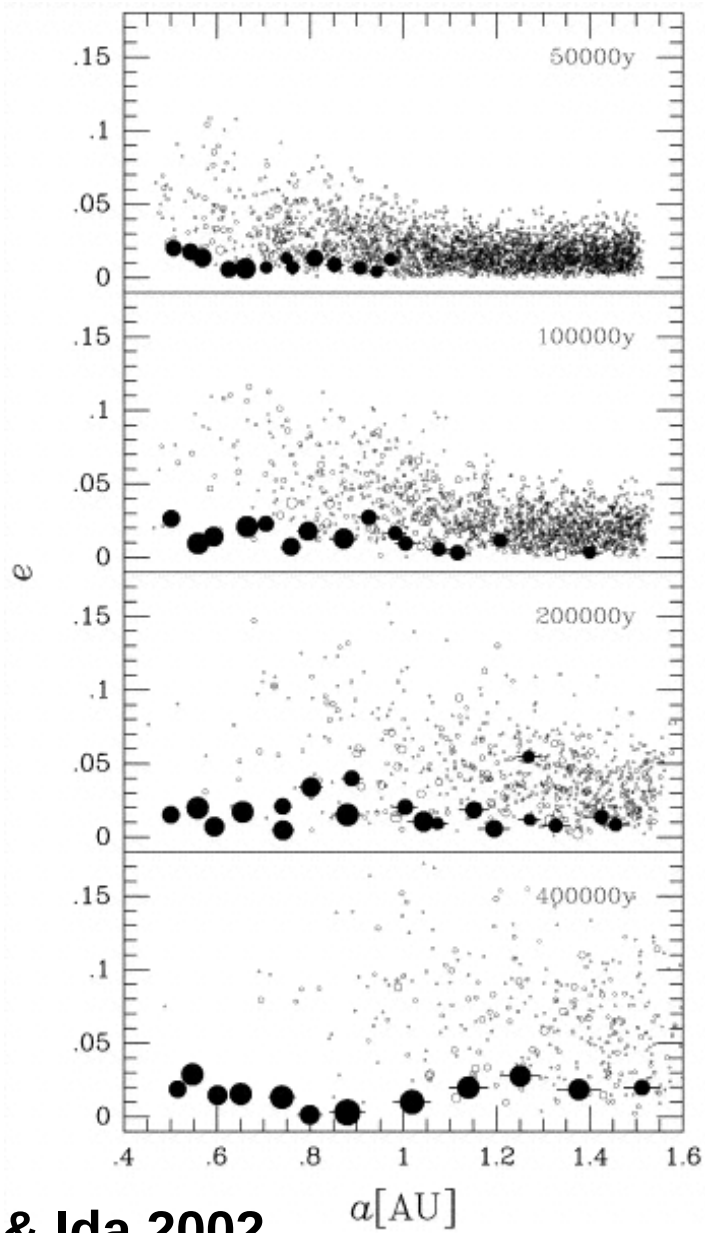
Oligarchic Growth

Particle in a box code



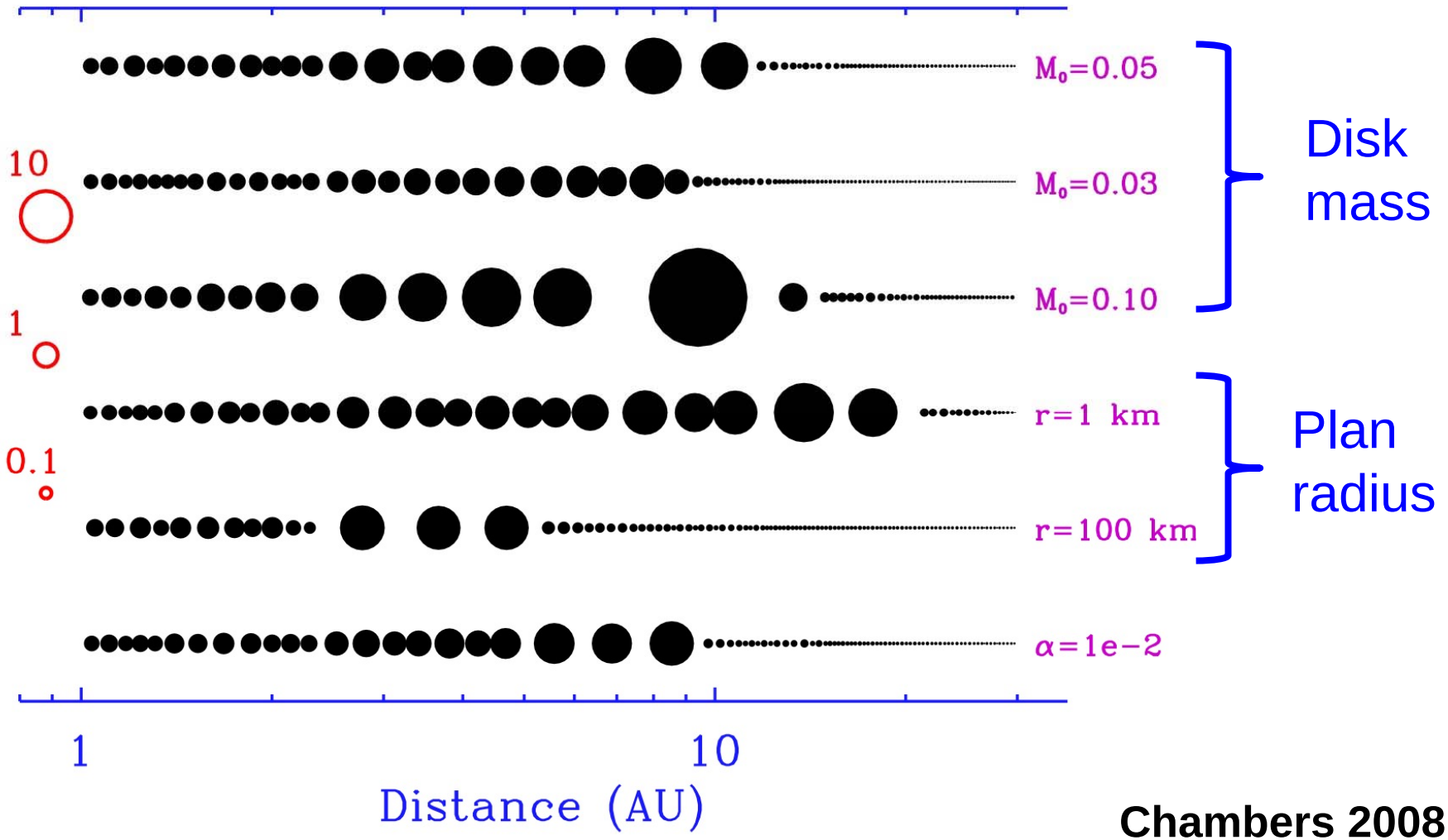
Weidenschilling et al. 1997

N-body code



Kokubo & Ida 2002

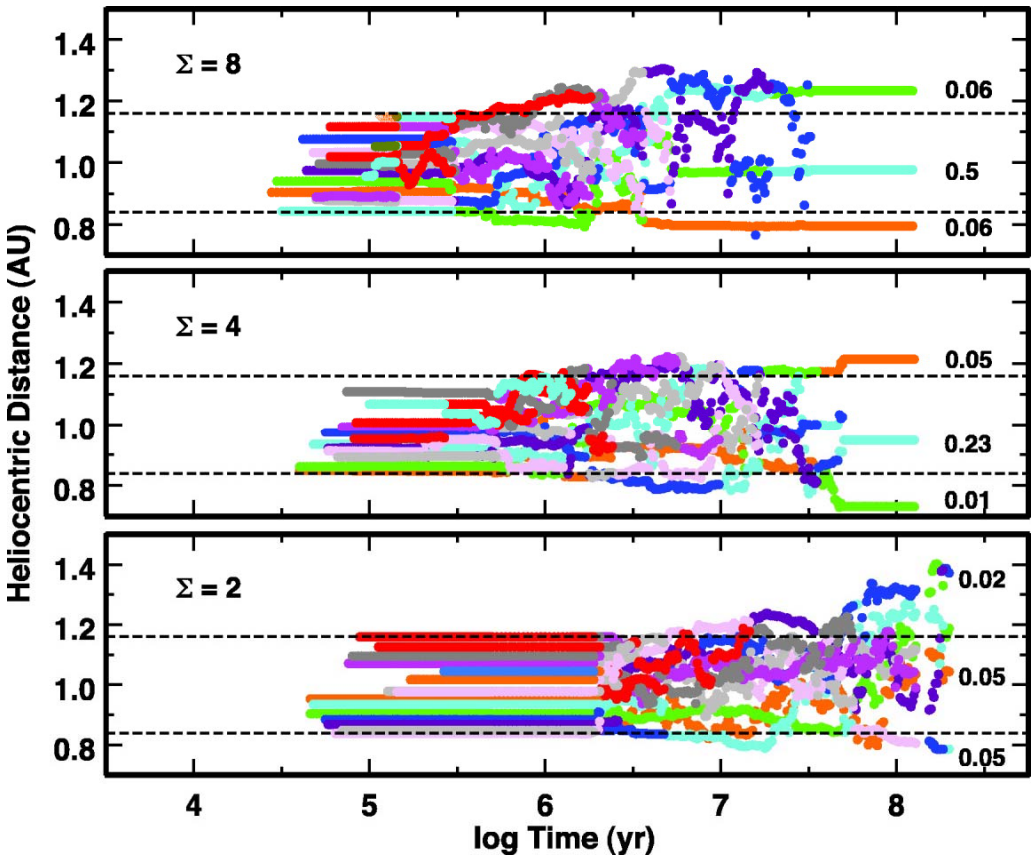
Oligarchic Growth



Chambers 2008

Late Stage Growth

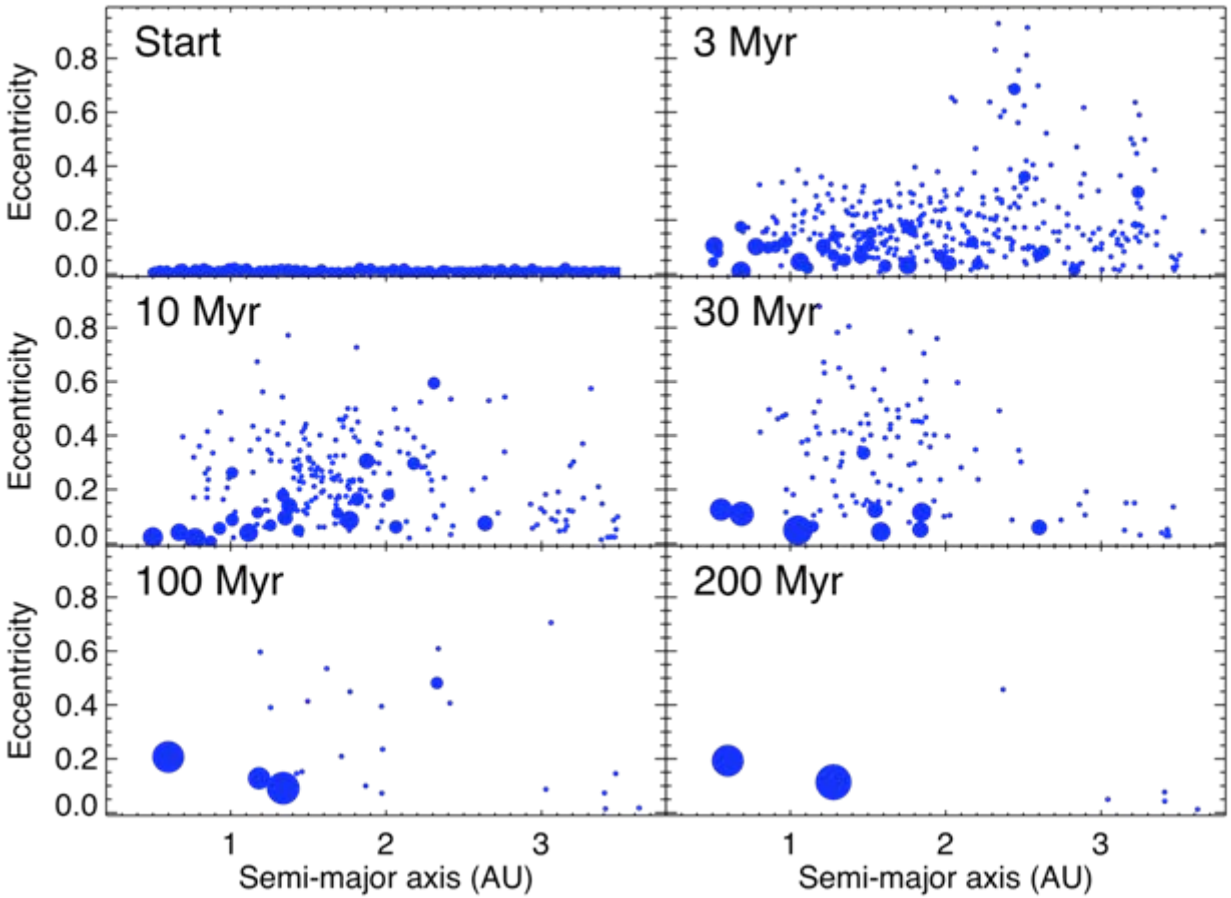
Transition from Oligarchic Growth



Kenyon & Bromley 2006

- Oligarchic growth ends when embryos contain about ½ mass.
- Dynamical friction becomes weak.
- Embryo orbits become crossing.

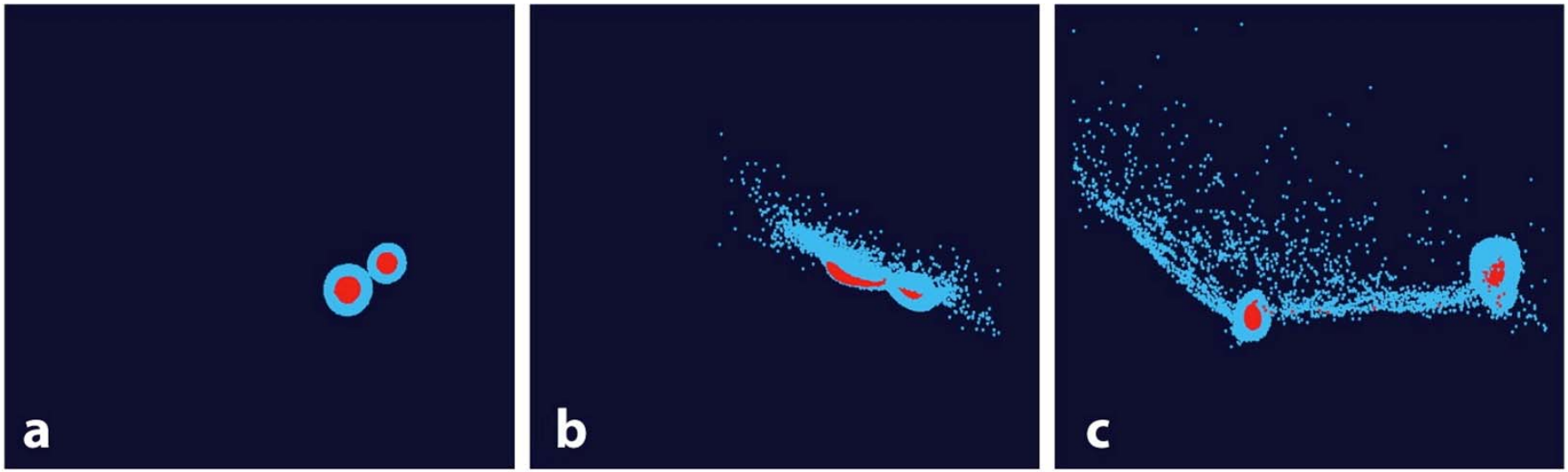
Late Stage Growth



- Growth is slow.
- Punctuated by giant impacts.
- Dynamical friction still operates.

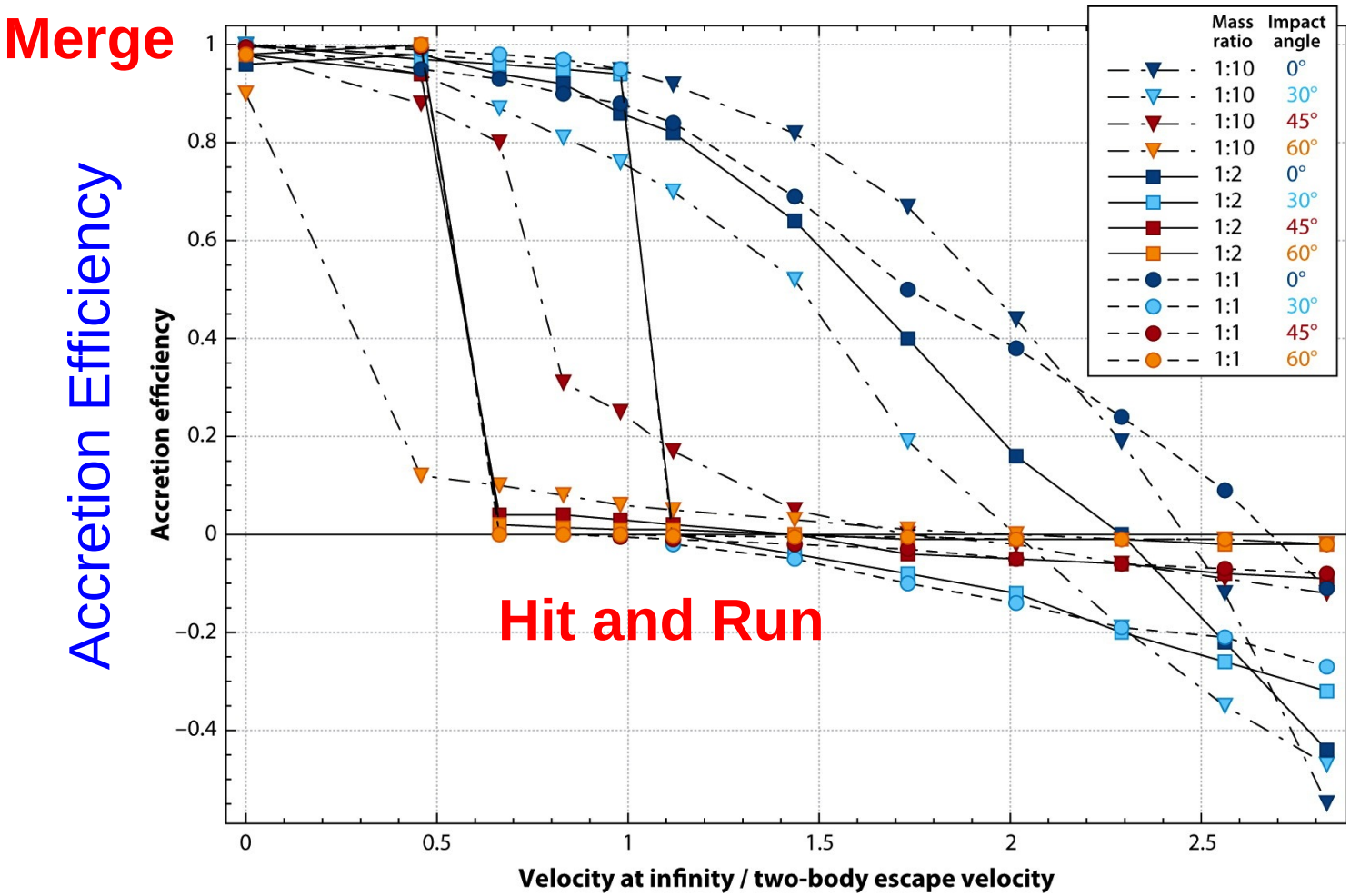
Chambers & Asphaug 2010

Hit and Run Collisions



Asphaug 2009

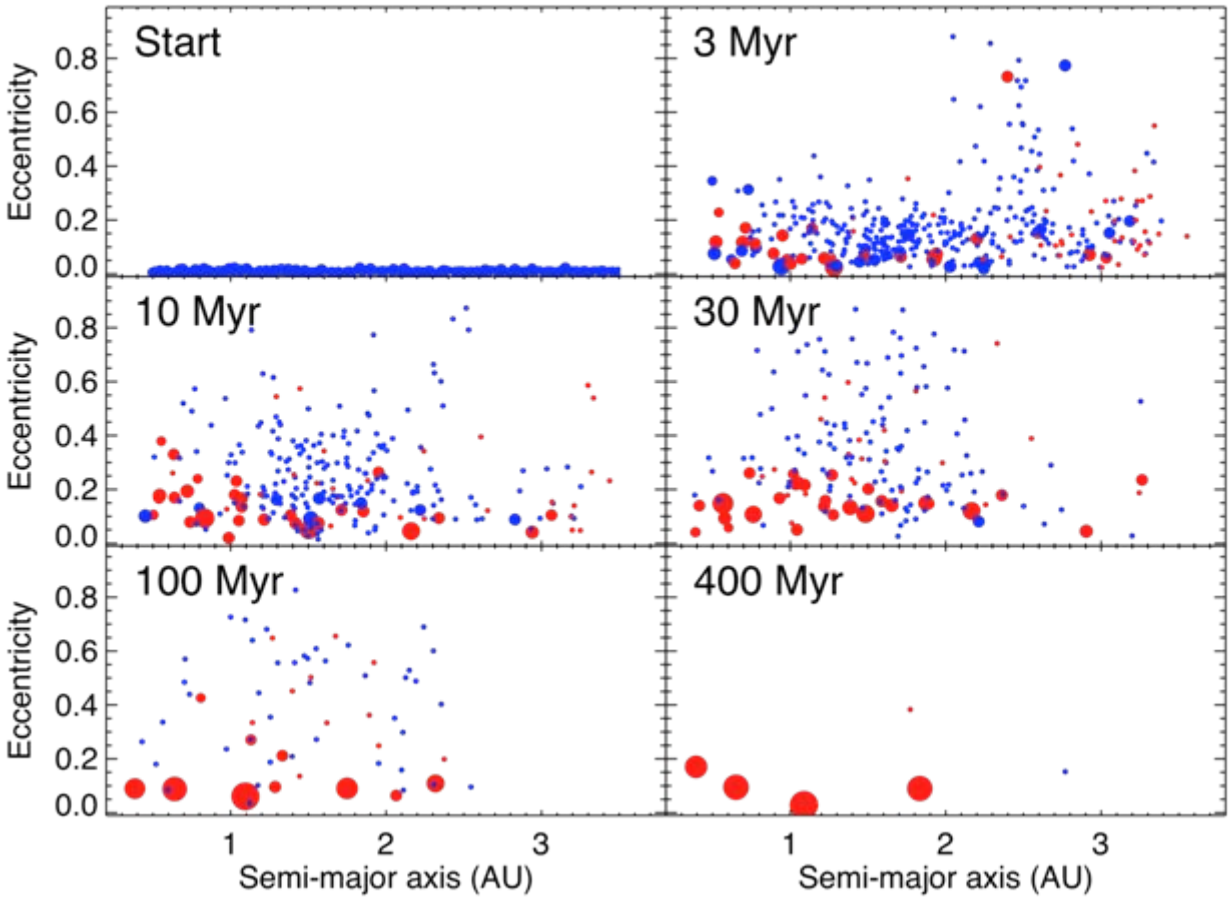
Hit and Run Collisions



Velocity at Infinity

Asphaug 2009

Late Stage Growth



Chambers & Asphaug 2010

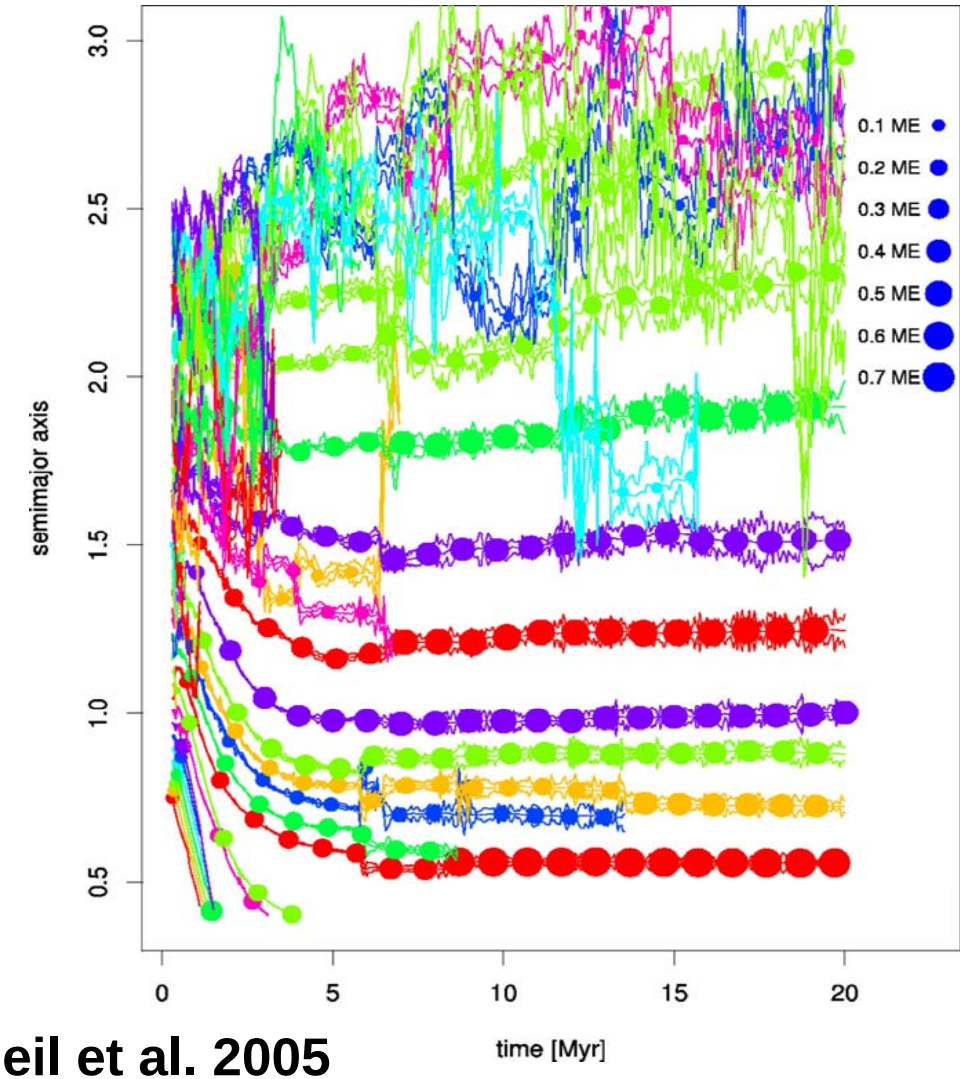
Pristine

Hit and run

- Most embryos undergo hit & run collisions.
- Growth is slowed further.

Type I Migration

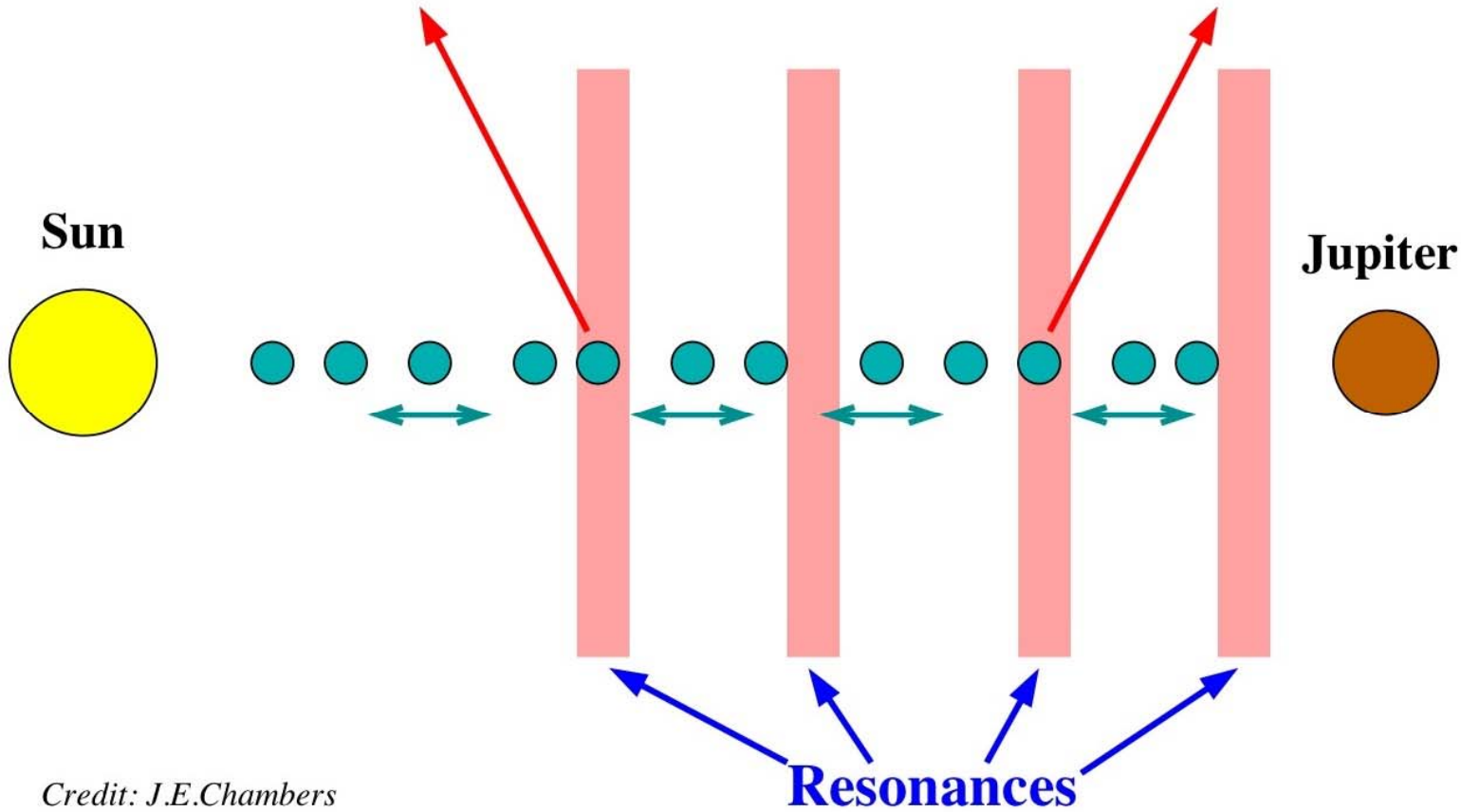
Artymowicz



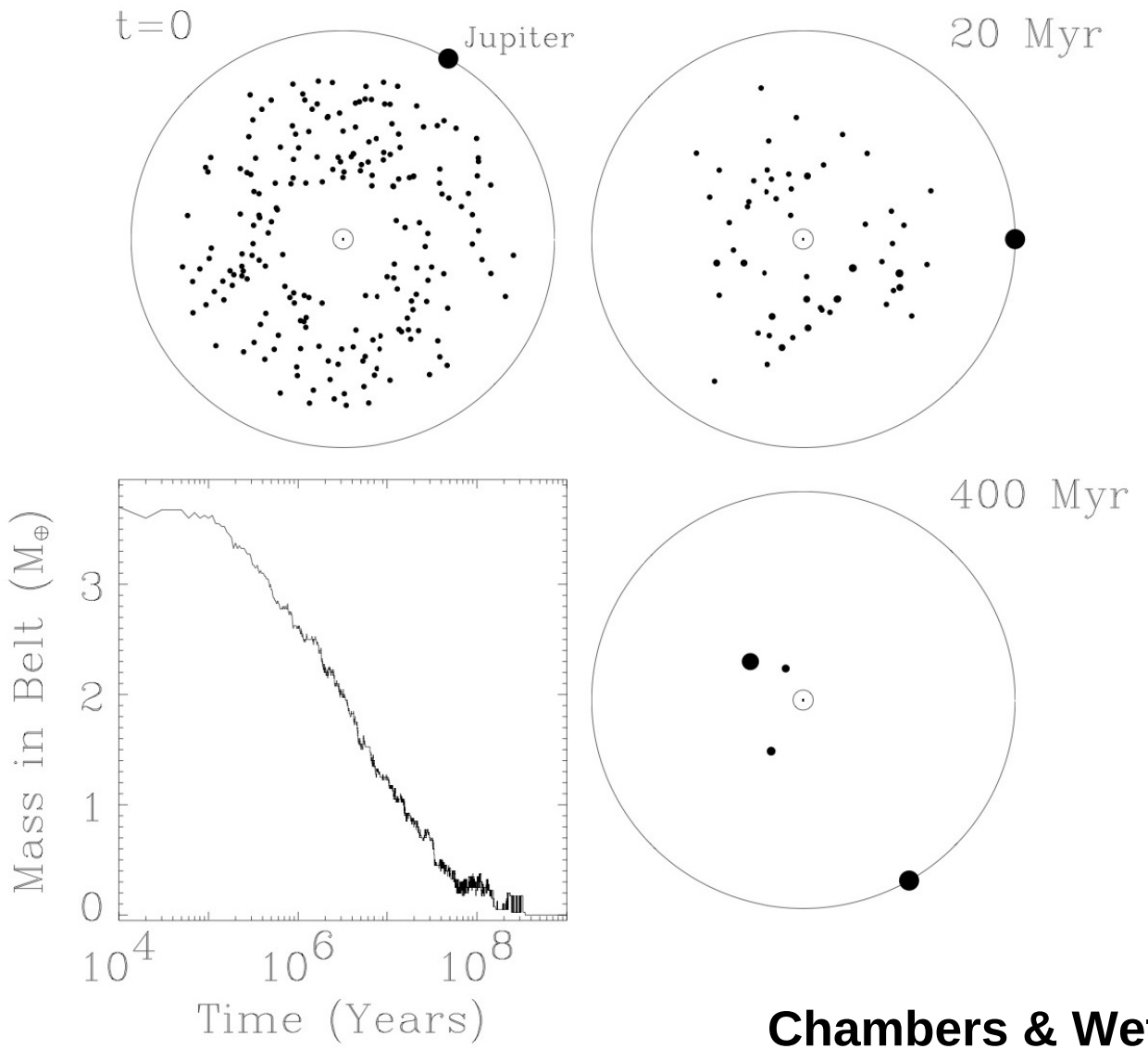
McNeil et al. 2005

Effect of Giant Planets

Clearing the Asteroid Belt

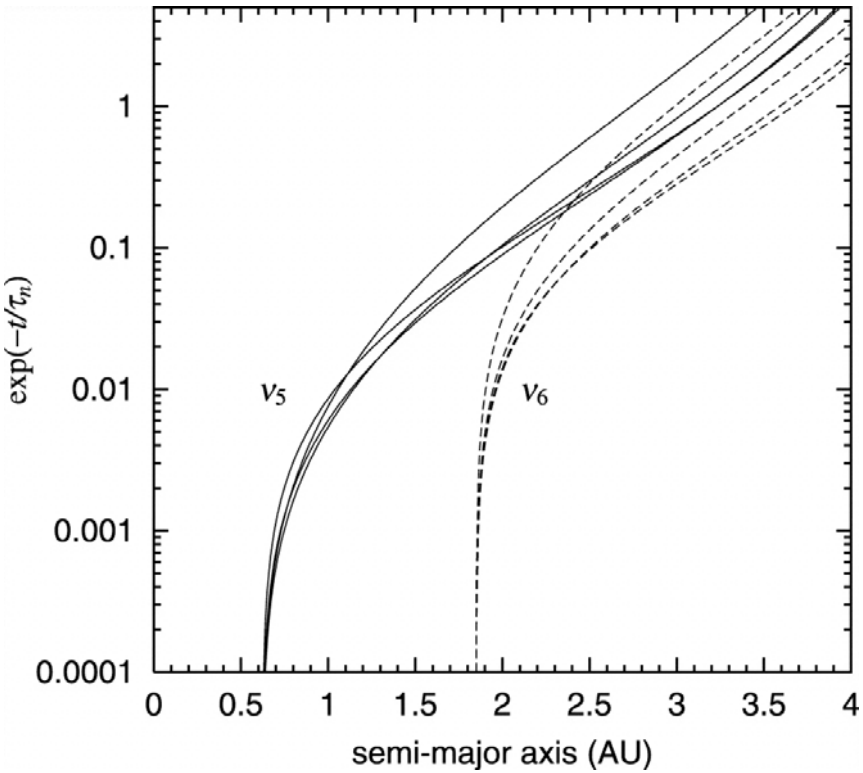


Clearing the Asteroid Belt



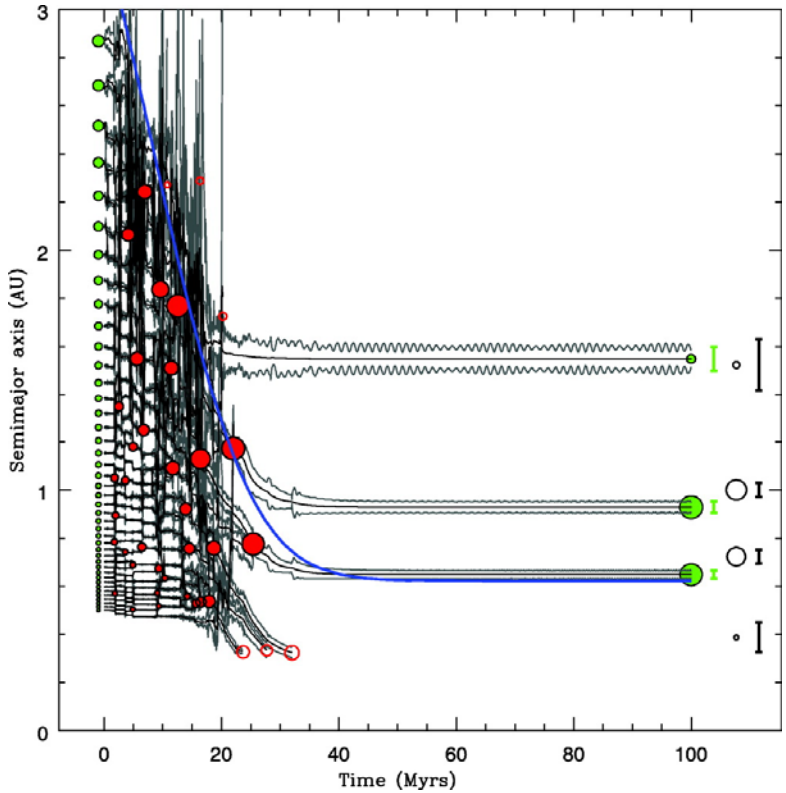
Chambers & Wetherill 2001

Sweeping Secular Resonances: ``Dynamical Shake-Up'' Model



Nagasawa et al. 2005

Distance (AU)

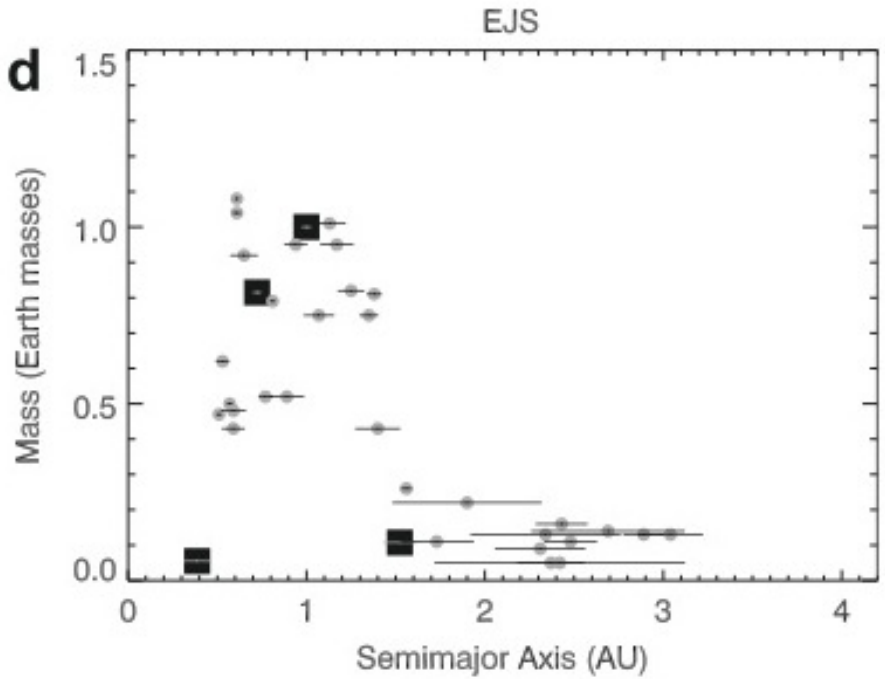


Time (My)

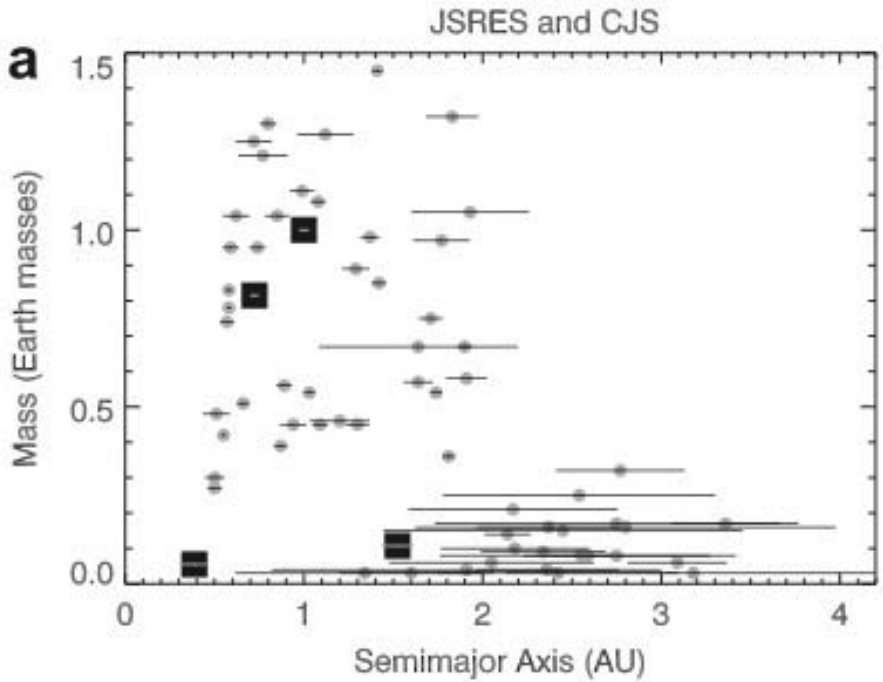
Thommes et al. 2008

Orbits of Jupiter + Saturn Affect Terrestrial Planets

Current Giant Planet Orbits

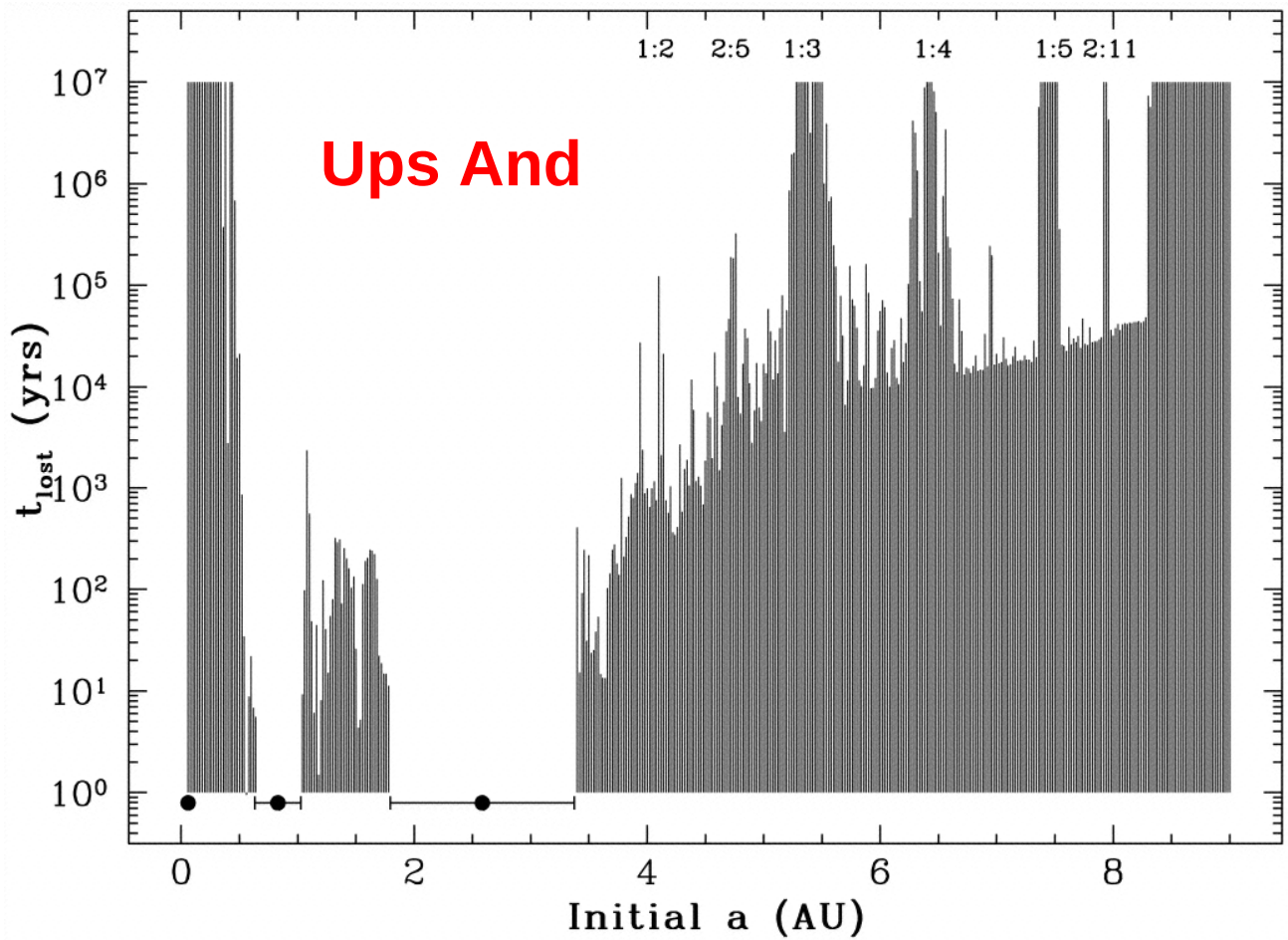


``Nice Model'' Orbits



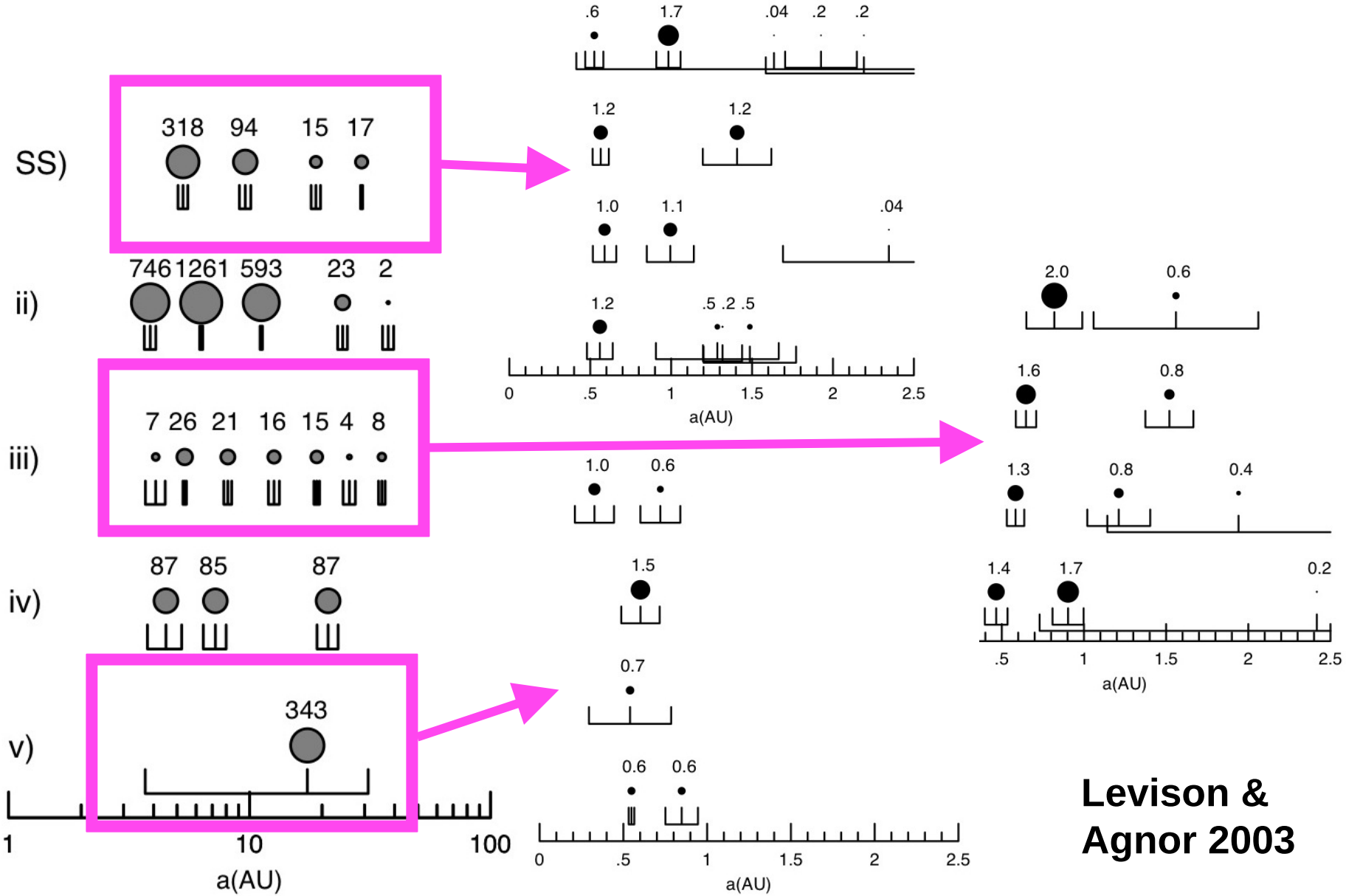
Raymond et al. (2009)

Giants Destabilize Nearby Terrestrial Planets



Lissauer & Rivera 2001

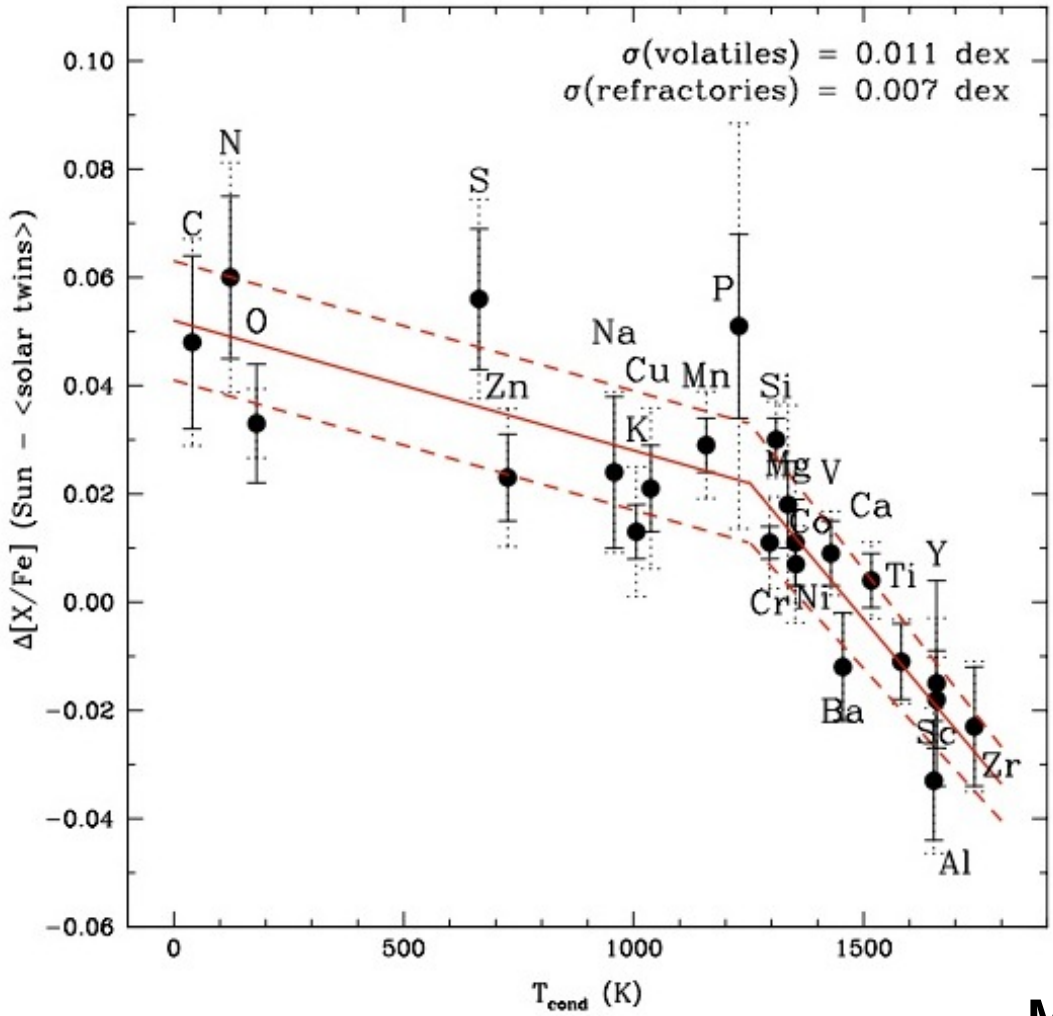
Giant Planet Configuration



Levison & Agnor 2003

Stellar Elemental Abundances and Terrestrial Planets

Solar Twin Abundances



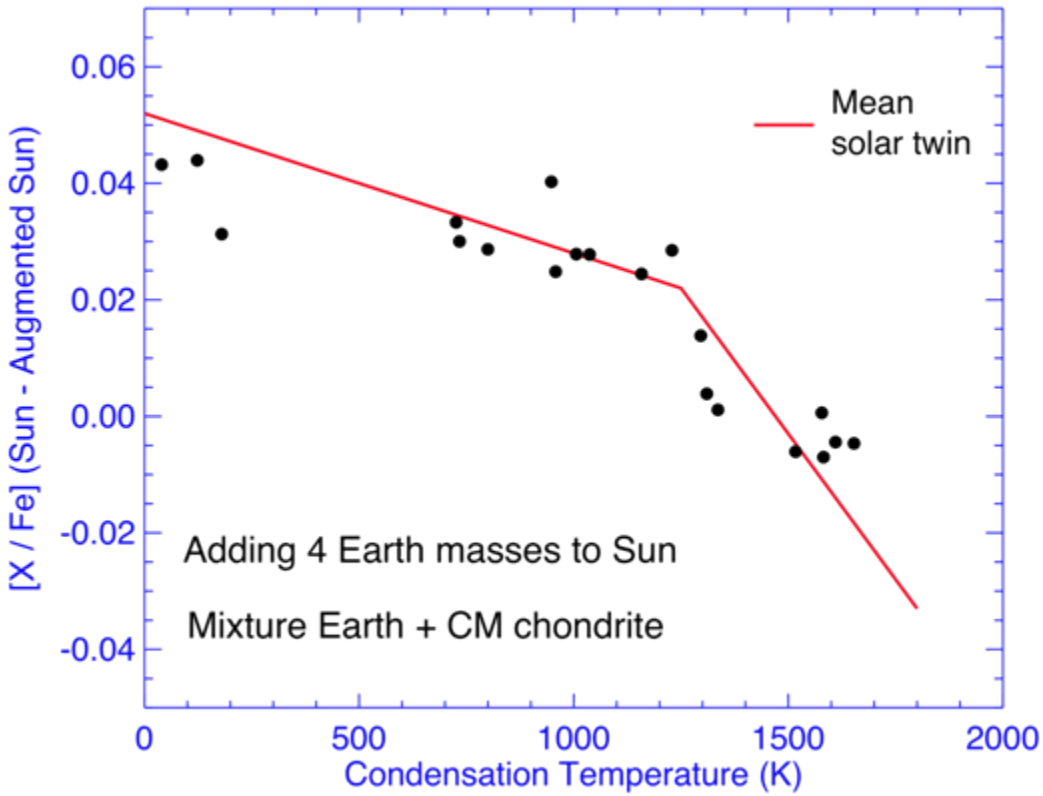
Abundance (Sun – solar twin)

Condensation Temperature

- Sun is depleted in refractory elements compared to most solar twins.
- Depletions correlated with condensation temperature

Melendez et al. 2009

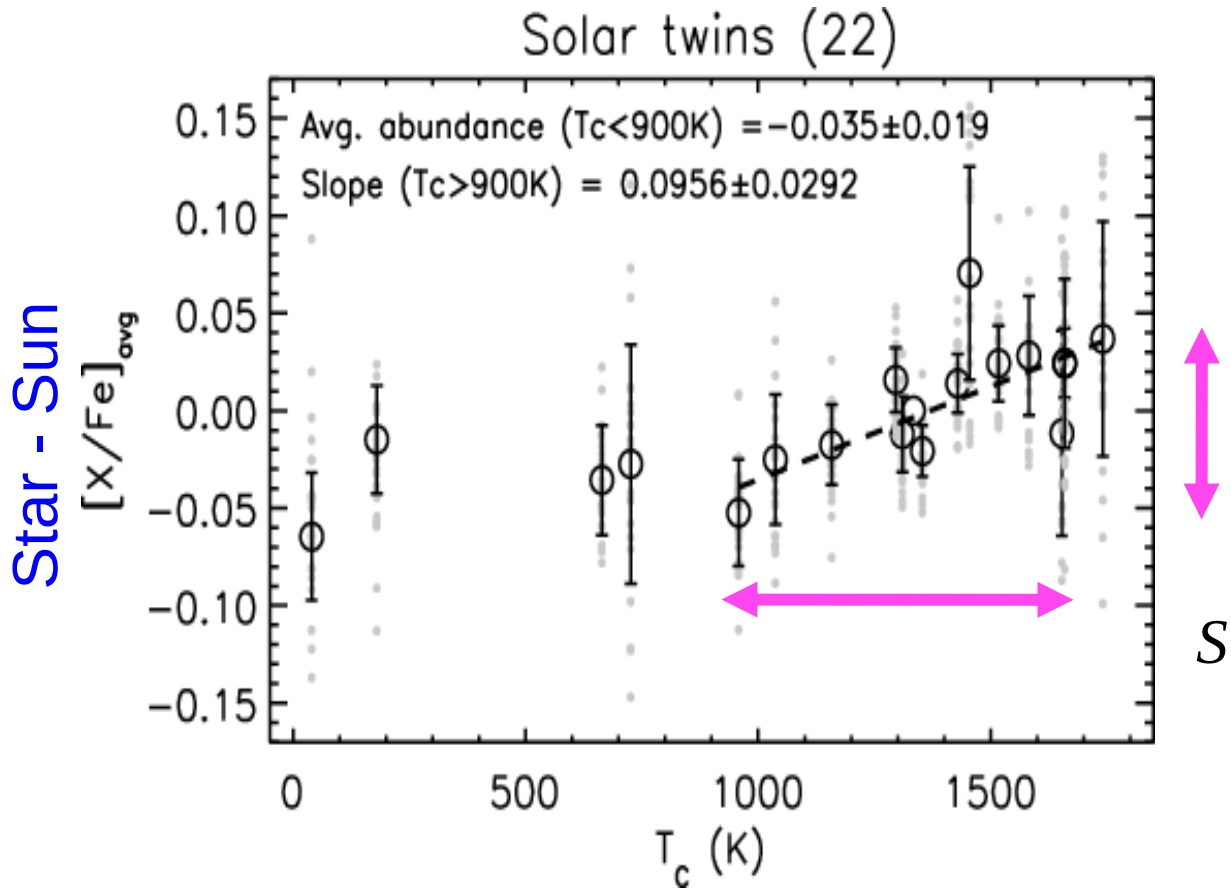
Signature of Terrestrial Planets?



Chambers 2010b

- Solar depletion may be due to mass in terrestrial planets + mass ejected from inner disk.
- Depletion must be limited to solar convection zone.

Abundance Slope

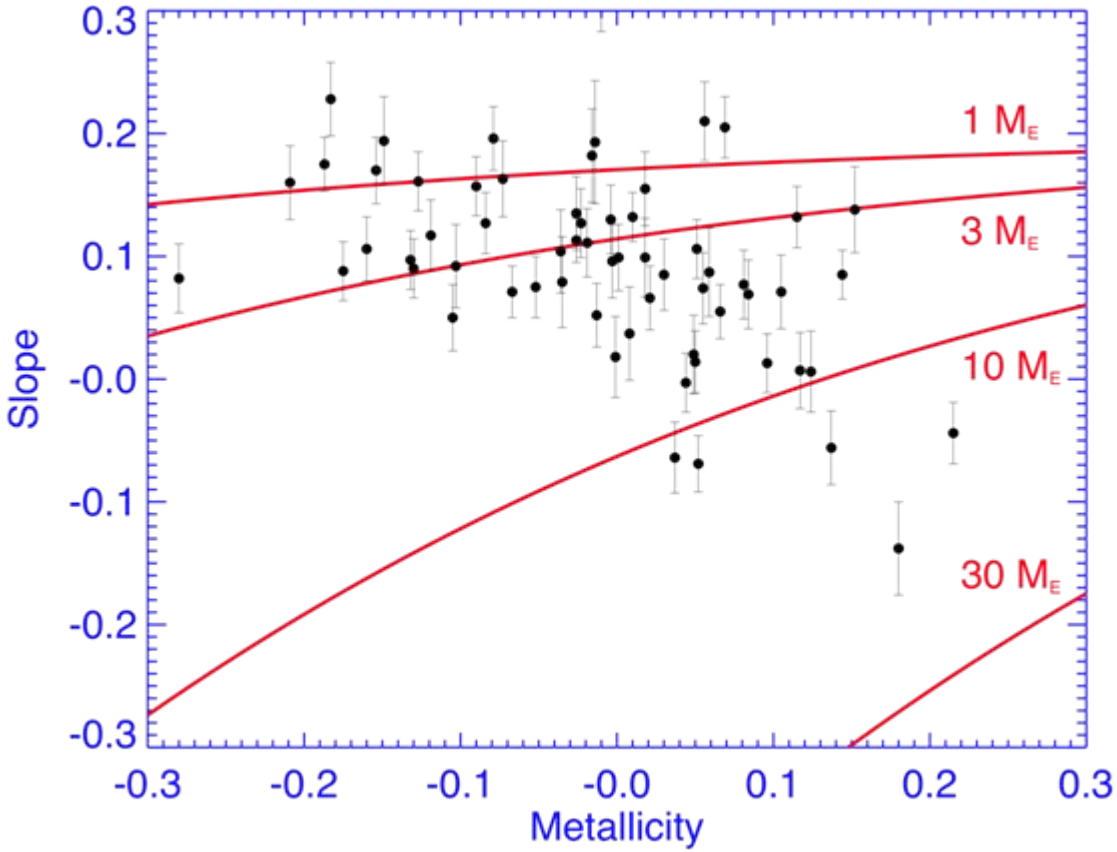


- Abundance slope for refractory elements:

$$S = \frac{[X/Fe] - [X_{900K}/Fe]}{T - 900K}$$

Ramirez et al. 2009

Missing Mass of Rock

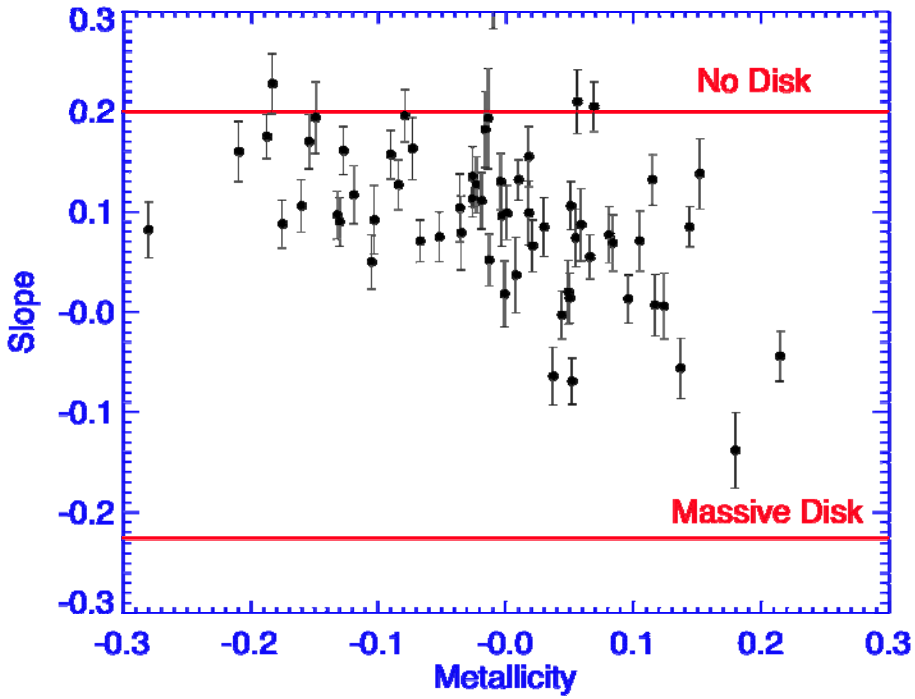


- Mass of rock missing from stellar CZ can be estimated given slope + metallicity.
- Missing rock is upper limit to mass of terrestrial planets.

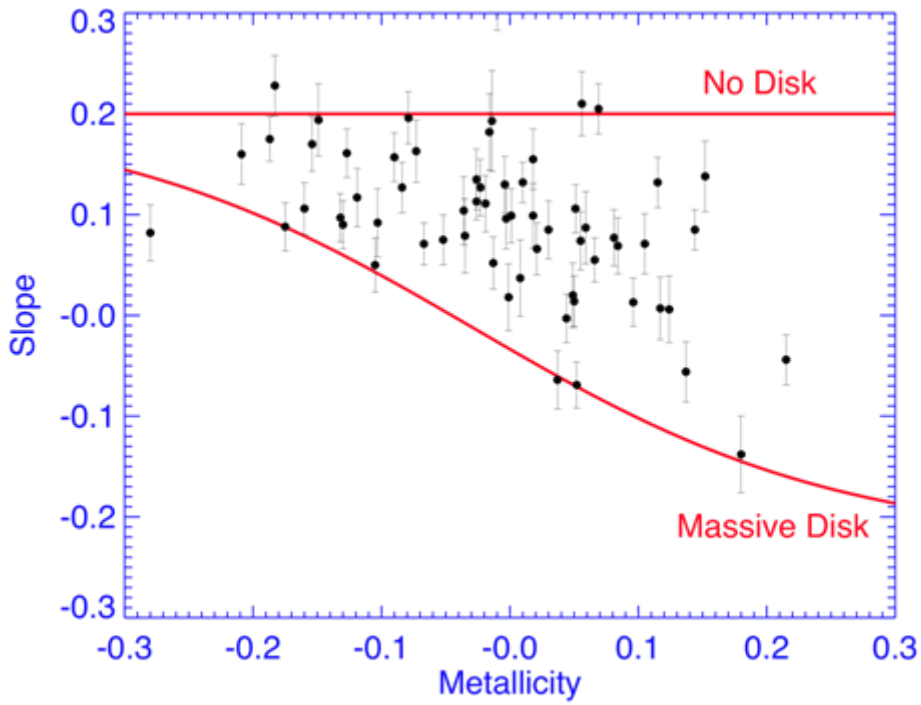
Chambers 2010b
data: Ramirez et al. 2009

Planetesimal Formation Depends on Metallicity *Z*

Formation Independent of Z

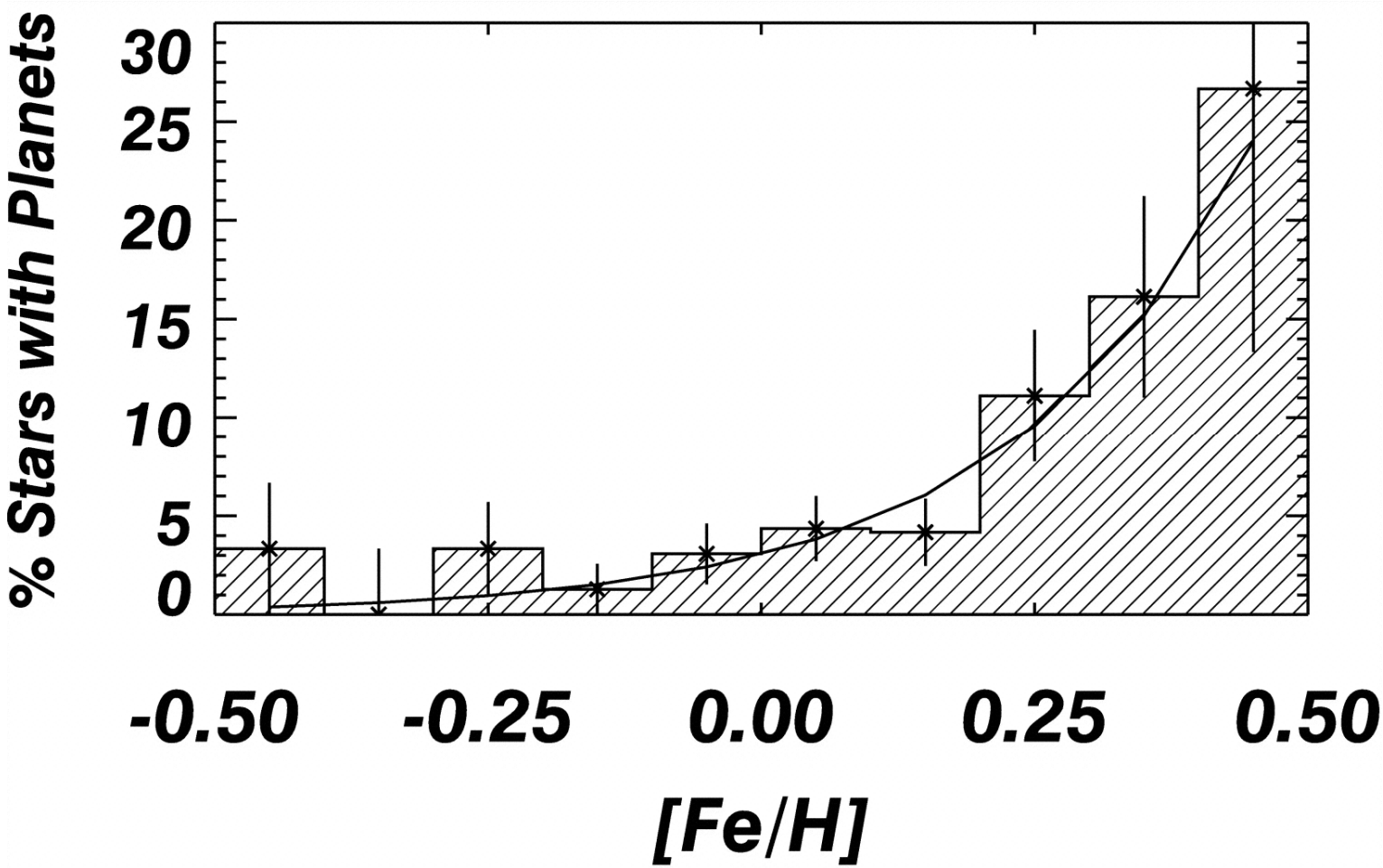


Formation Increases with Z



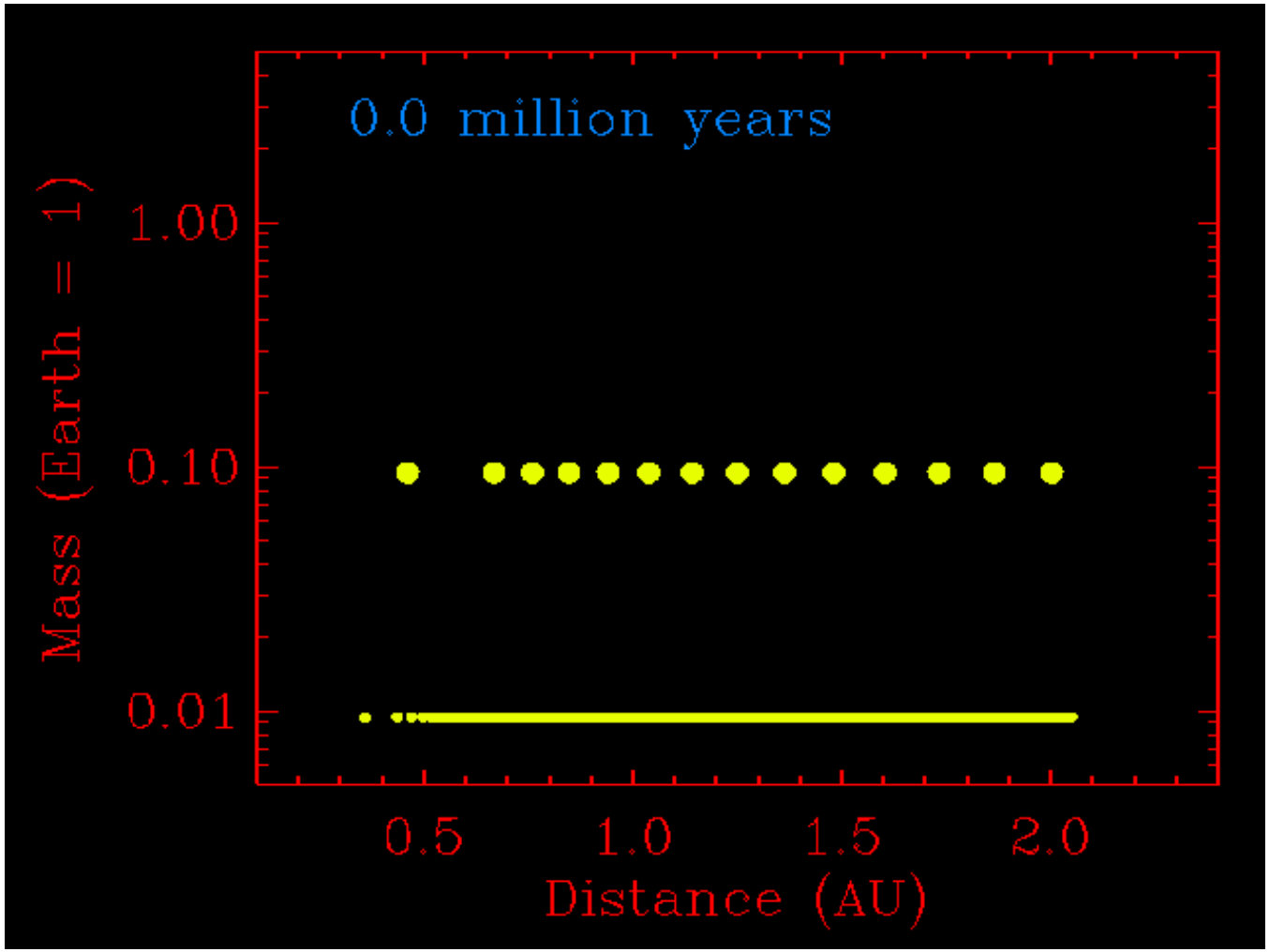
Chambers 2010b

Planet Metallicity Connection



Fischer & Valenti 2005

The End



Chambers 2001