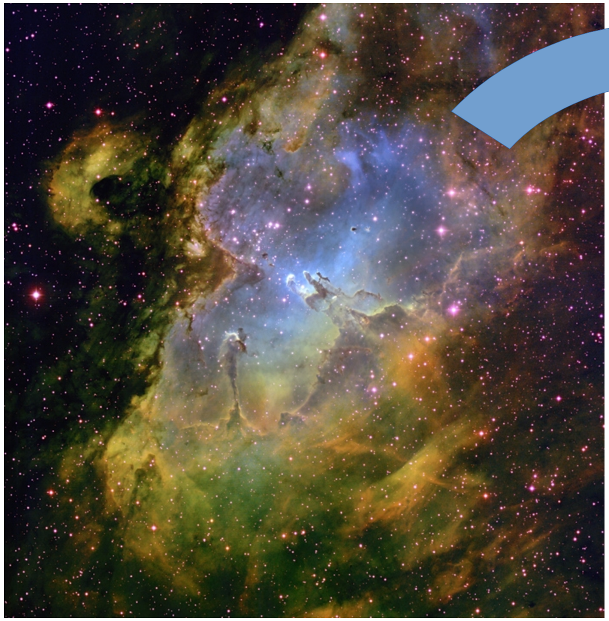
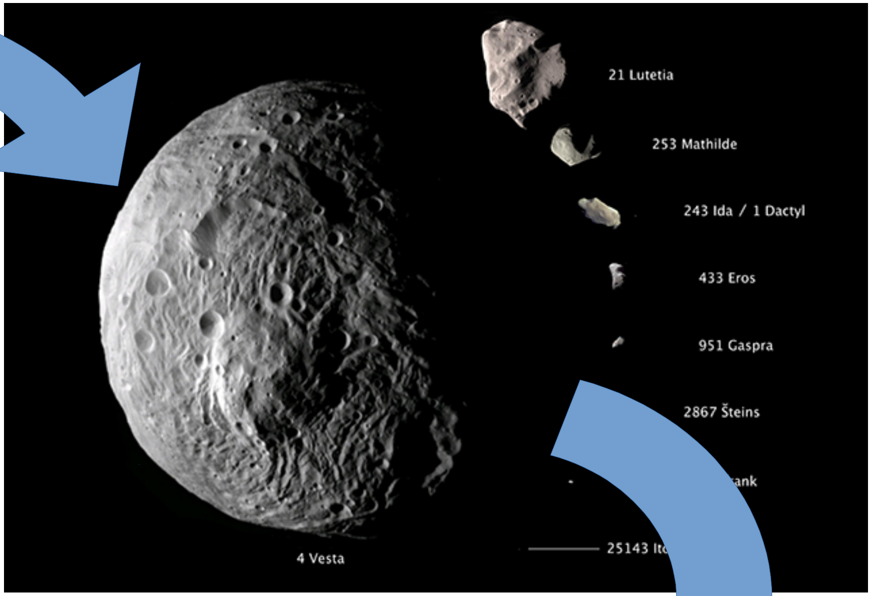
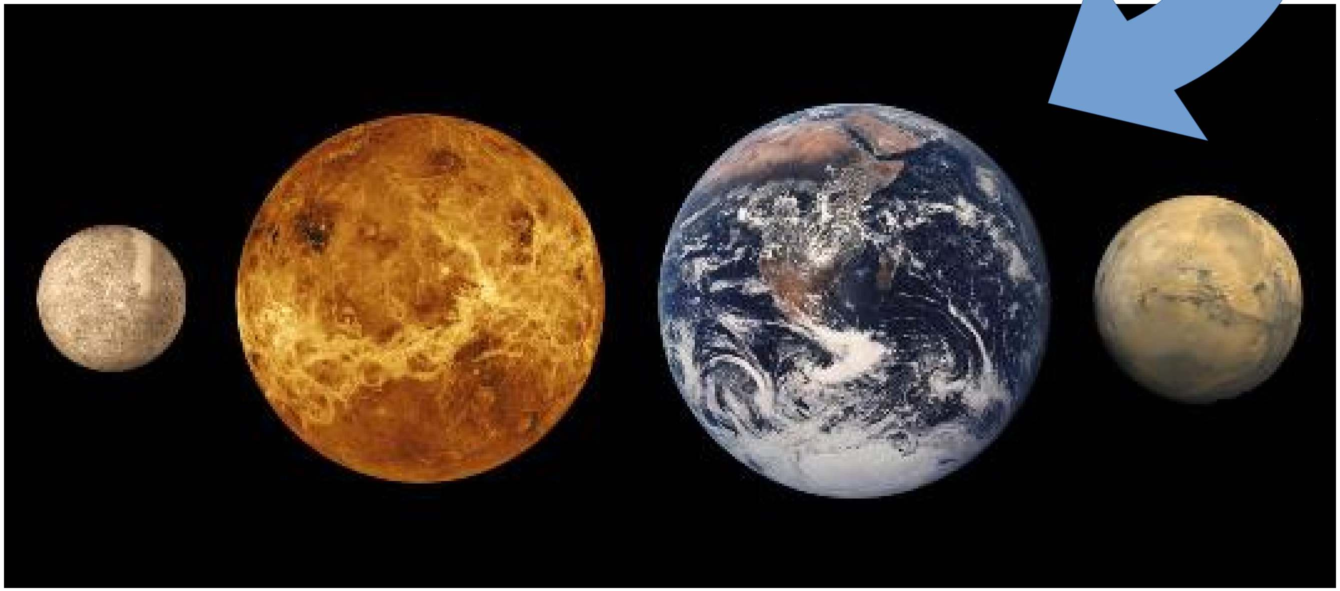
First Steps of Planet Formation

Katherine Kretke (NPP SSERVI Fellow)



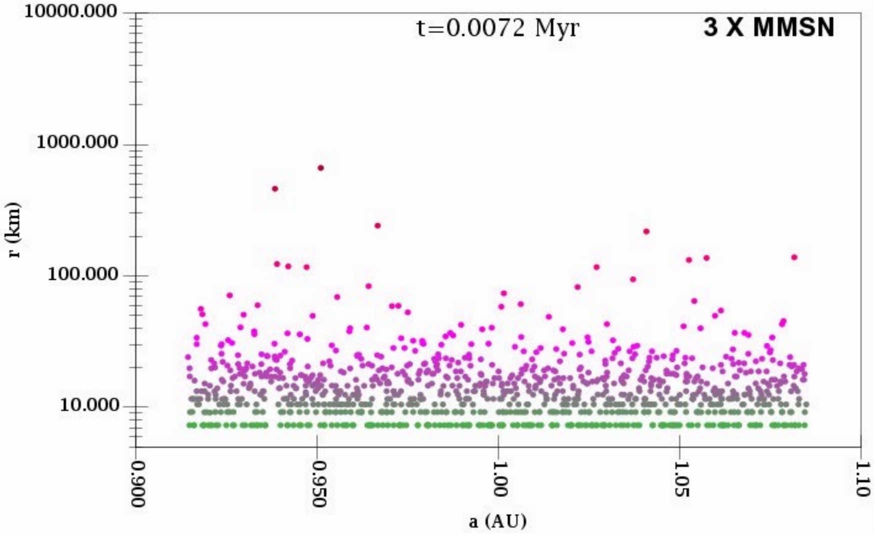

21 Lutetia
253 Mathilde
243 Ida / 1 Dactyl
433 Eros
951 Gaspra
2867 Šteins
4 Vesta

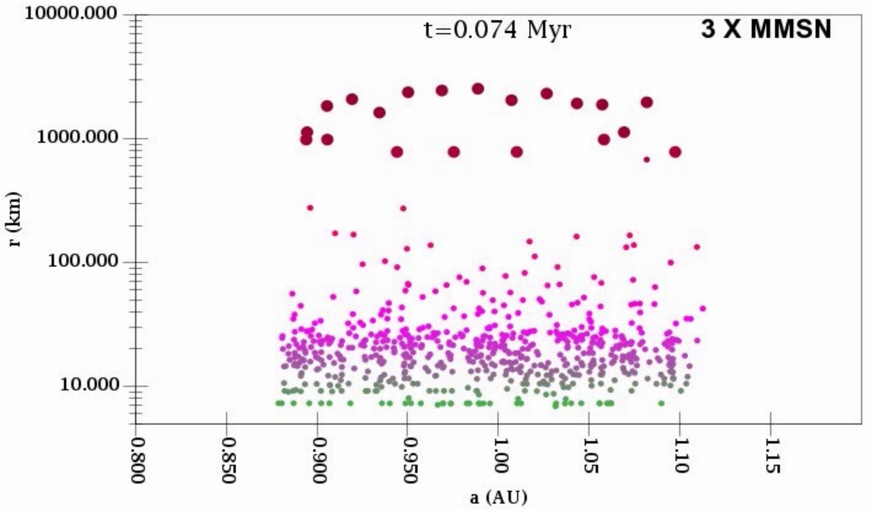


Classical Model - Planetesimals

Runaway

Oligarchic



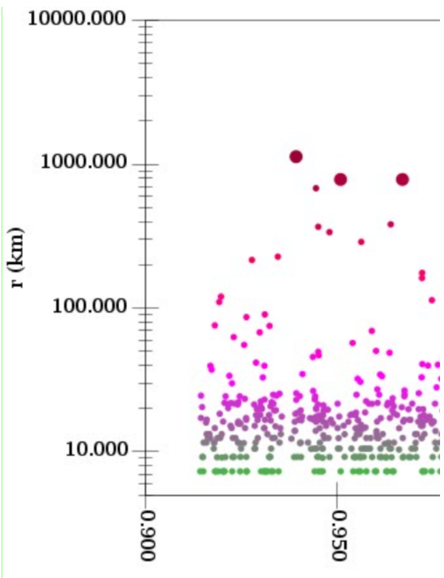


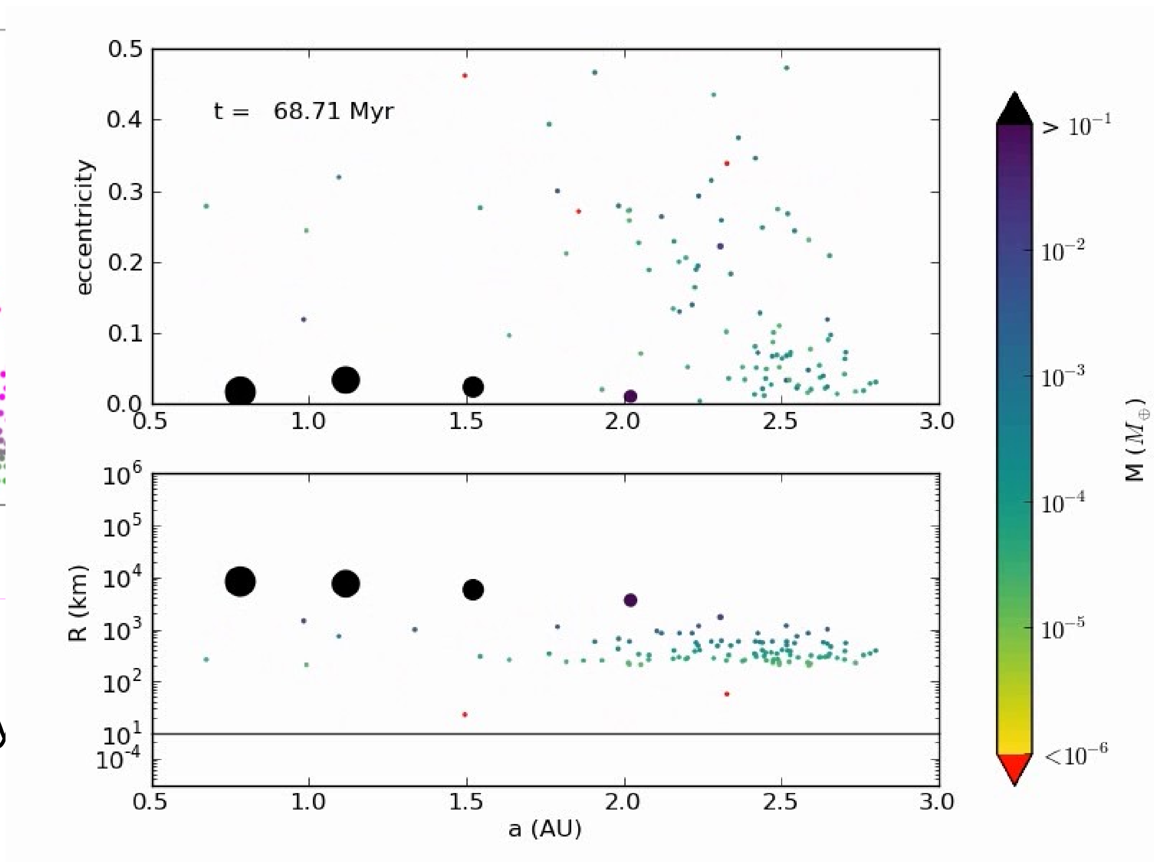
Mass Limited by isolation mass (as long as the planetesimals are cool).

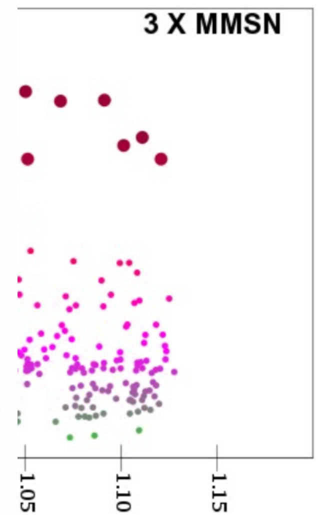
Classical Model - Planetesimals

Runaway

Oligarchic

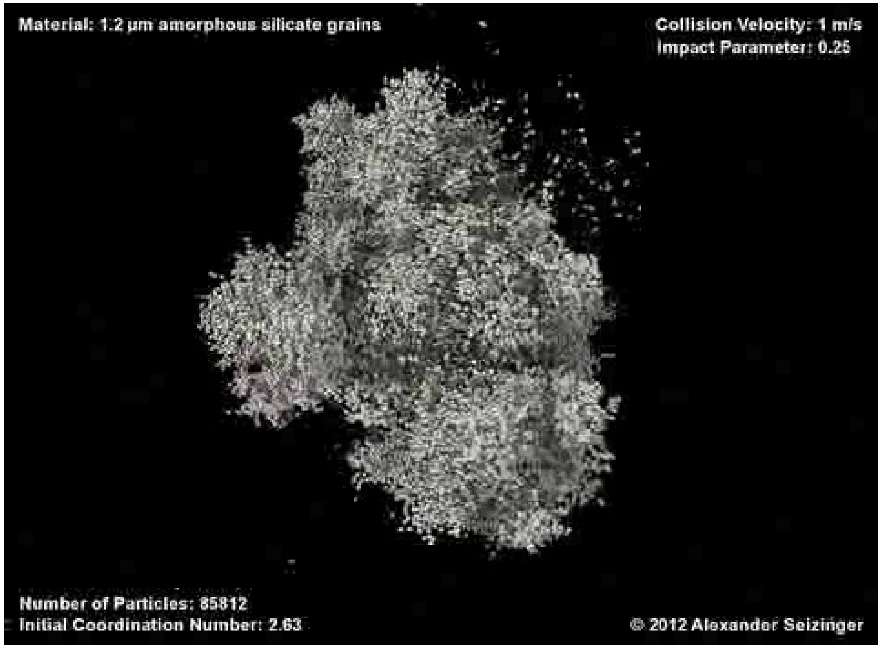






Mass Limited by

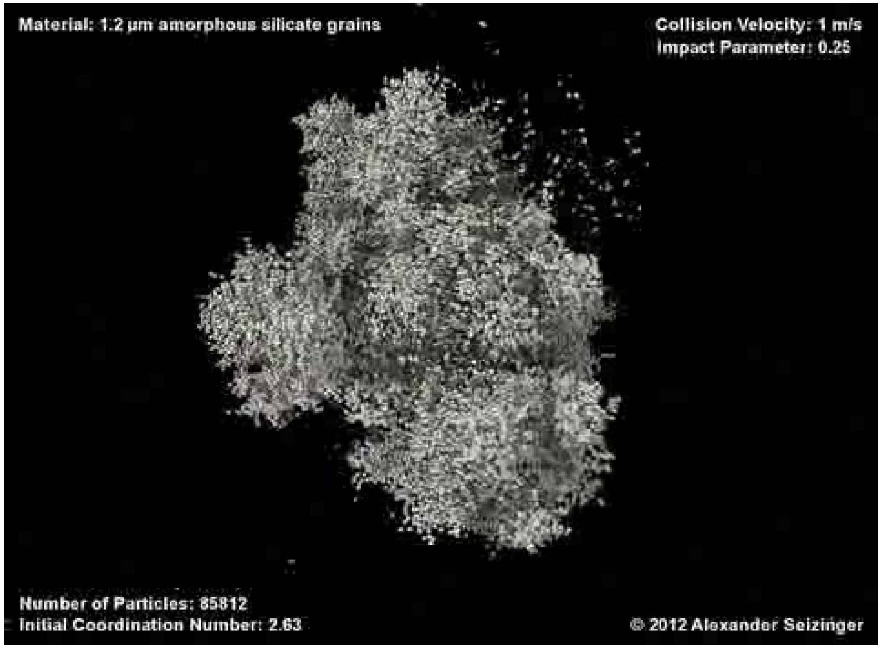
Growth of Dust



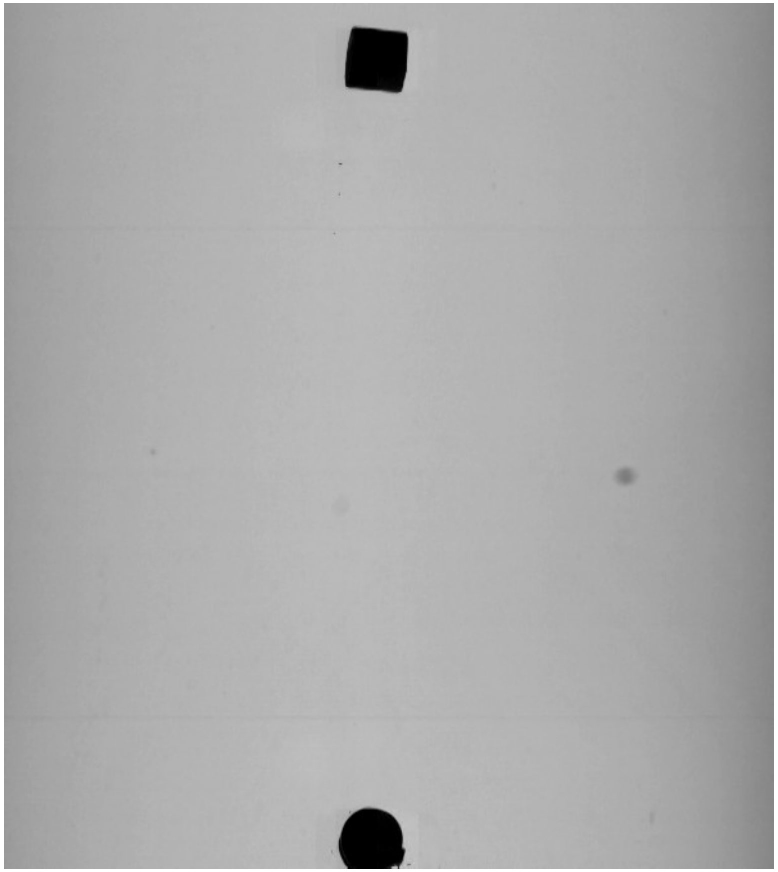
eg. Seizinger, Speith, Kley (2012)

e.g. Blum et al 2014

Growth of Dust

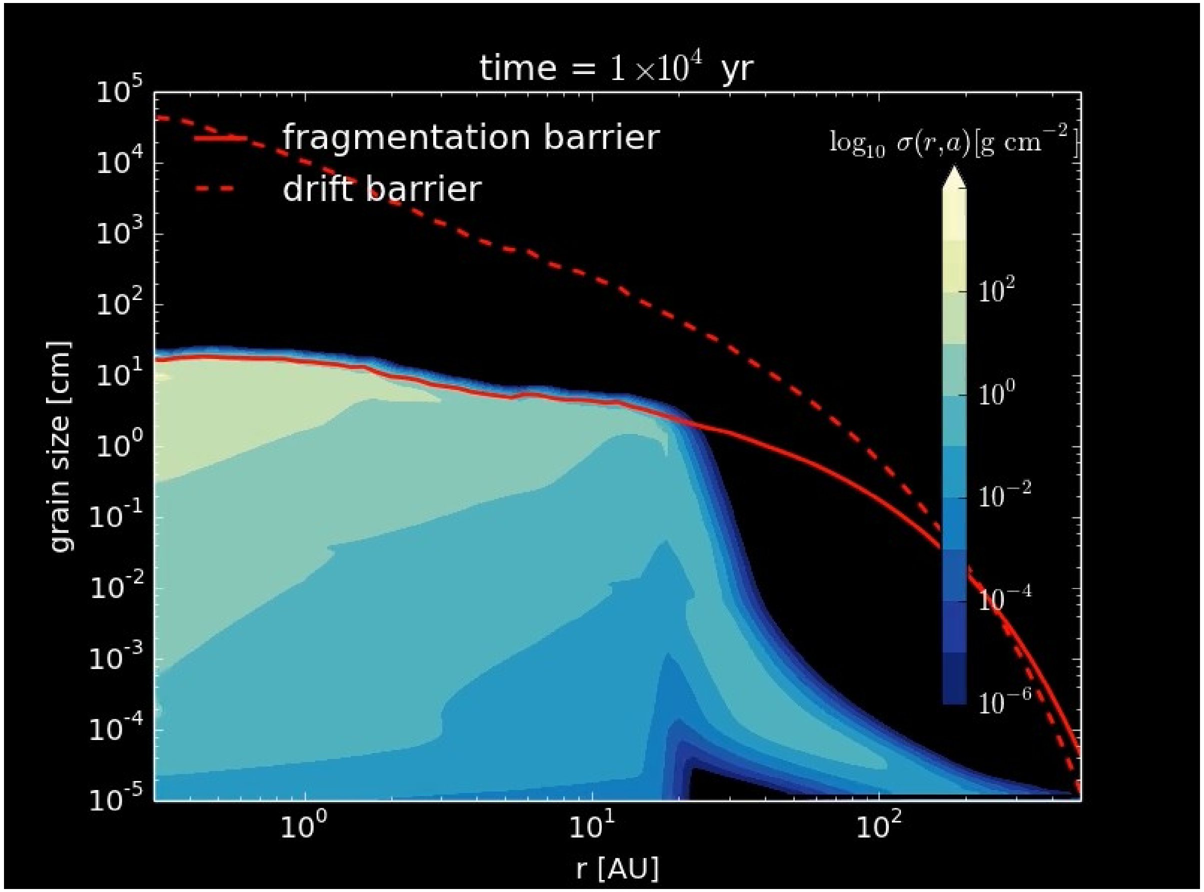


eg. Seizinger, Speith, Kley (2012)



e.g. Blum et al 2014

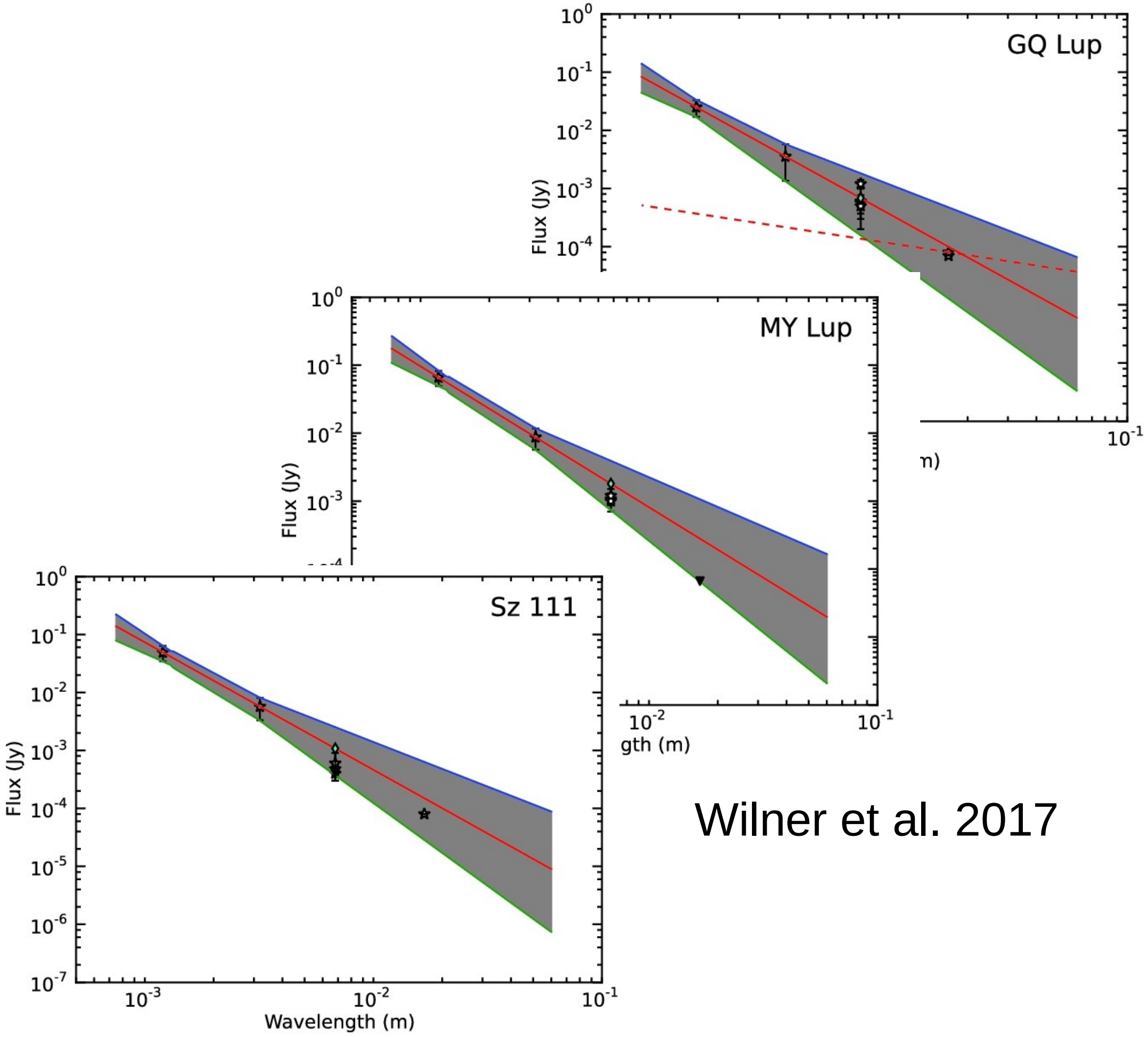
Challenges to Particle Growth



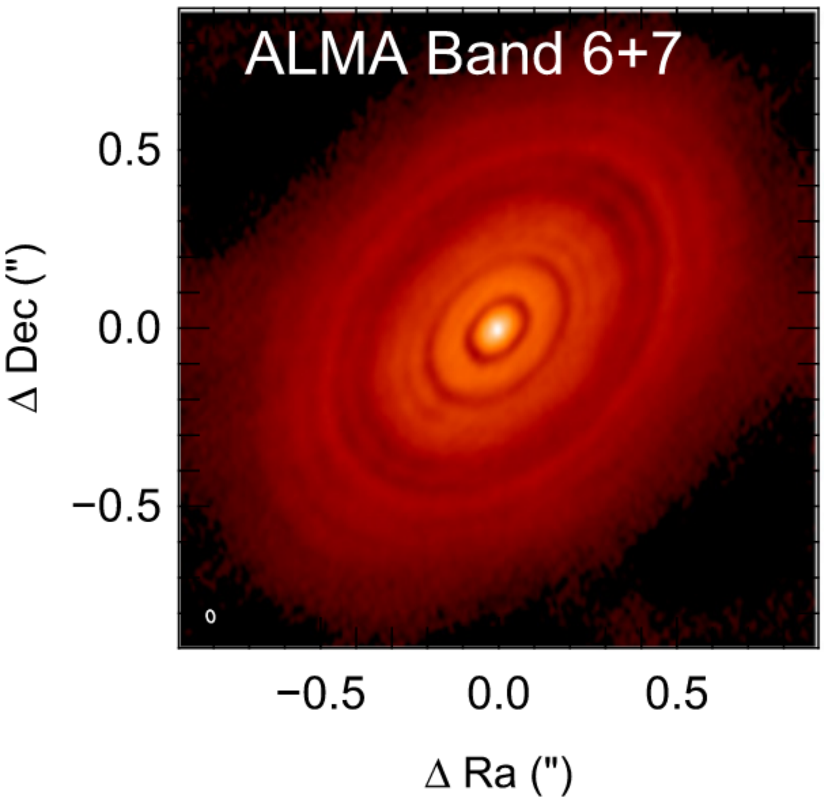
- Fragmentation
- Compaction & Bouncing
- Radial Drift

e.g. Birnstiel et al. (2012)

Observational Evidence of “pebbles”

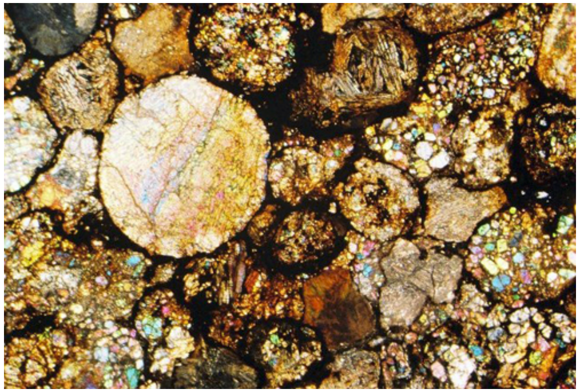


Wilner et al. 2017

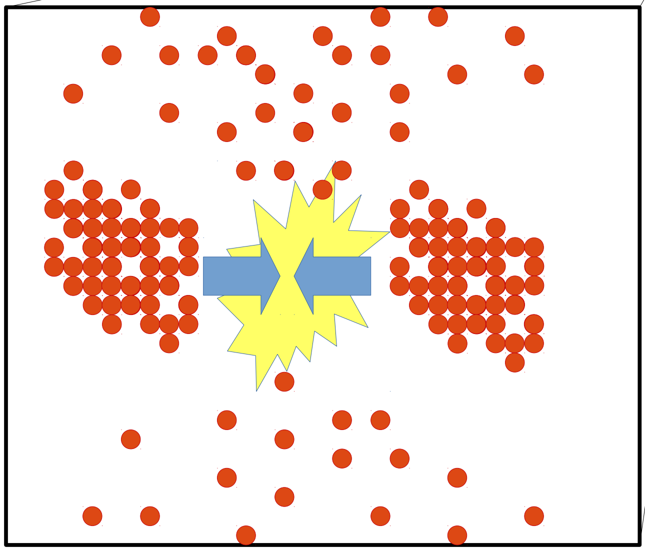


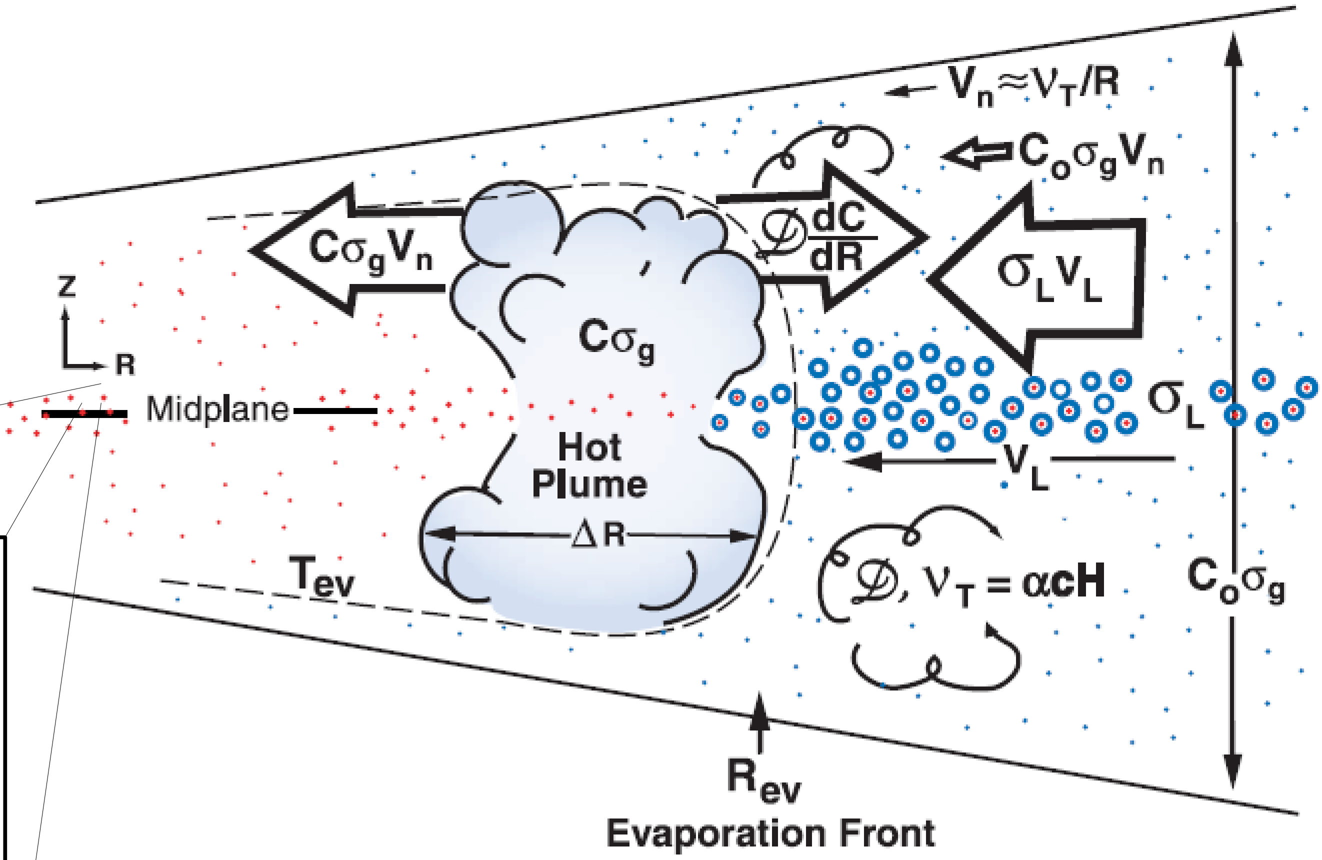
Pinte et al 2016

Volatiles and Drifting Pebbles



Bunch 2009

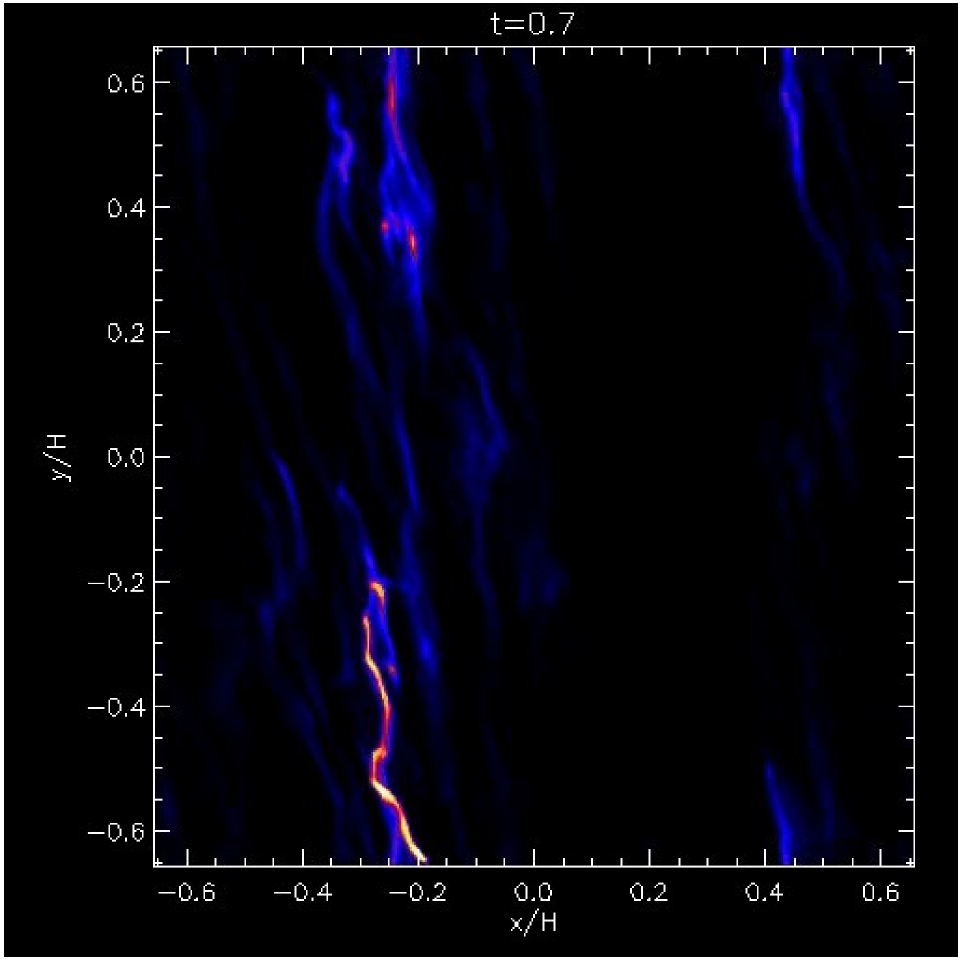




Cuzzi & Zahnle (2004)

In the inner regions, article growth is likely limited by **fragmentation**

Pebbles may clump and form planetesimals!



ϕ

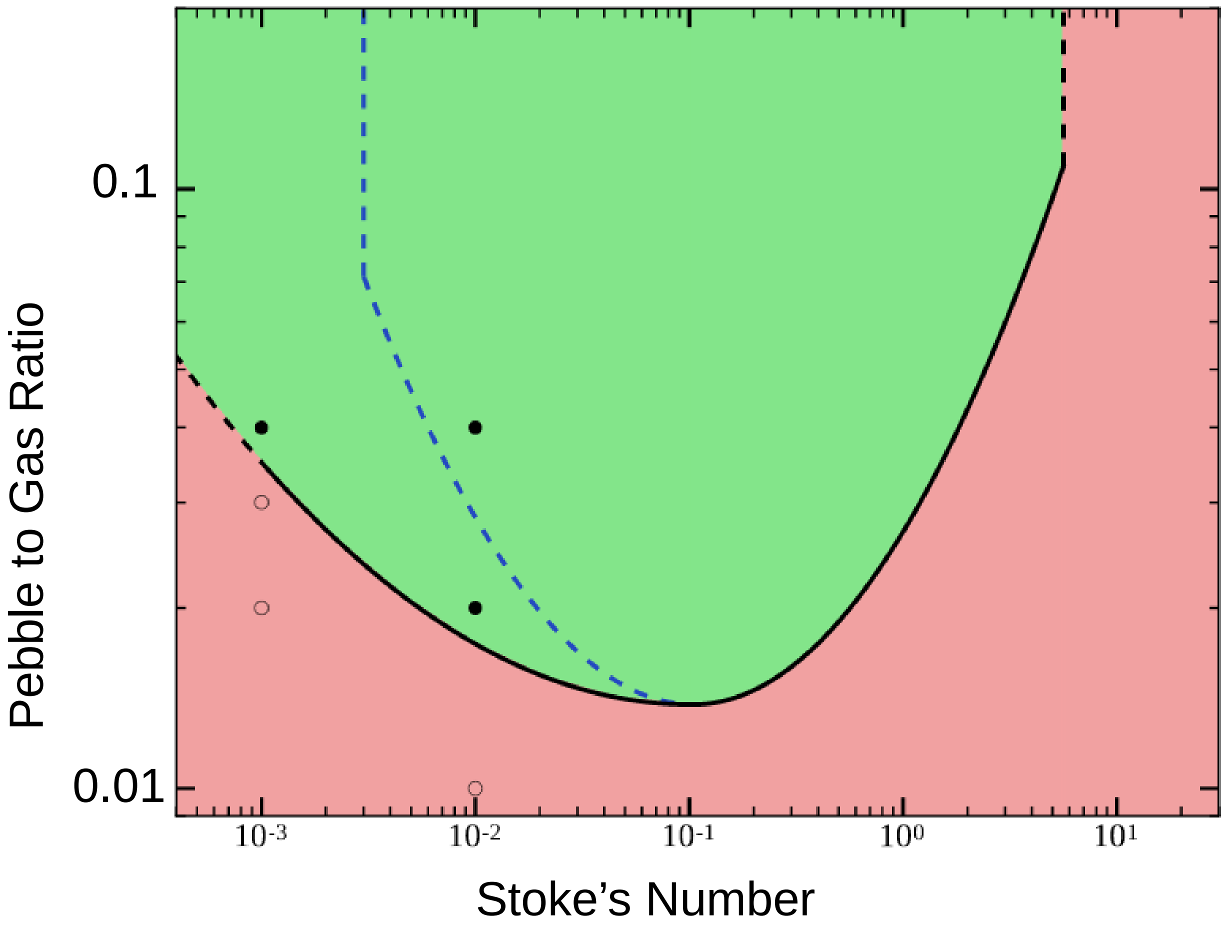
To the sun

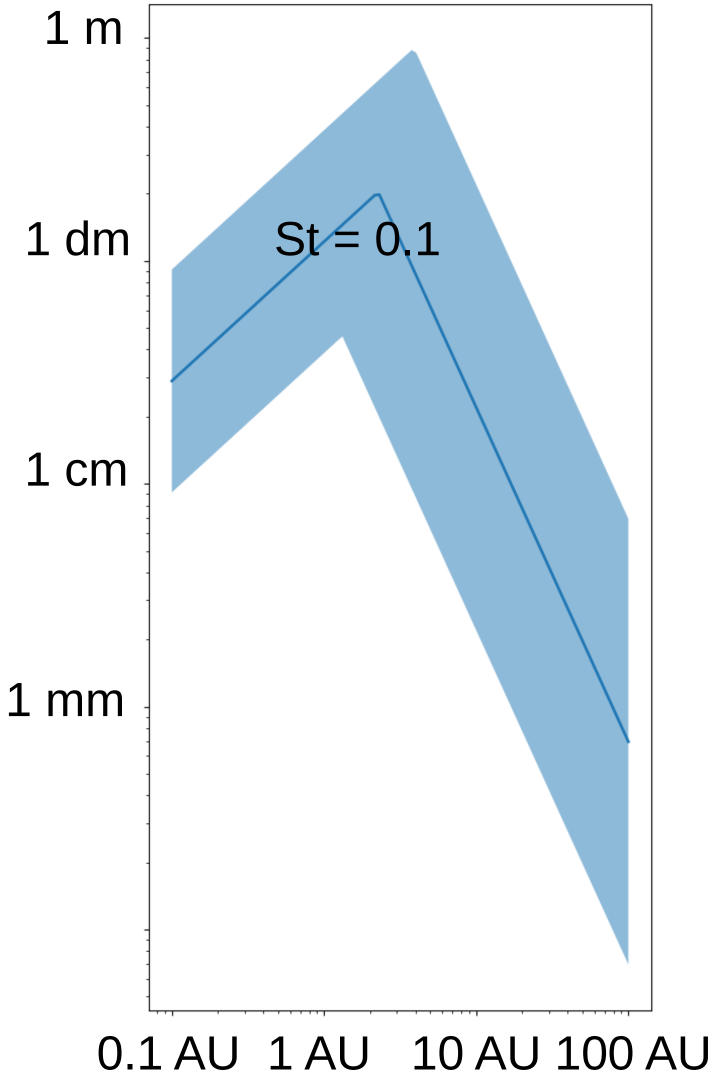
r

Streaming Instability:
Youdin & Goodman (2005)
Also turbulent clumping e.g. Cuzzi (2010)

e.g. Johansen et al. (2007)

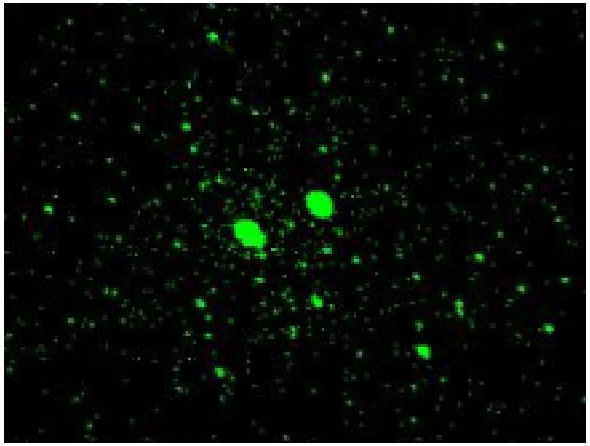
The Streaming Instability Needs a lot of Pebbles



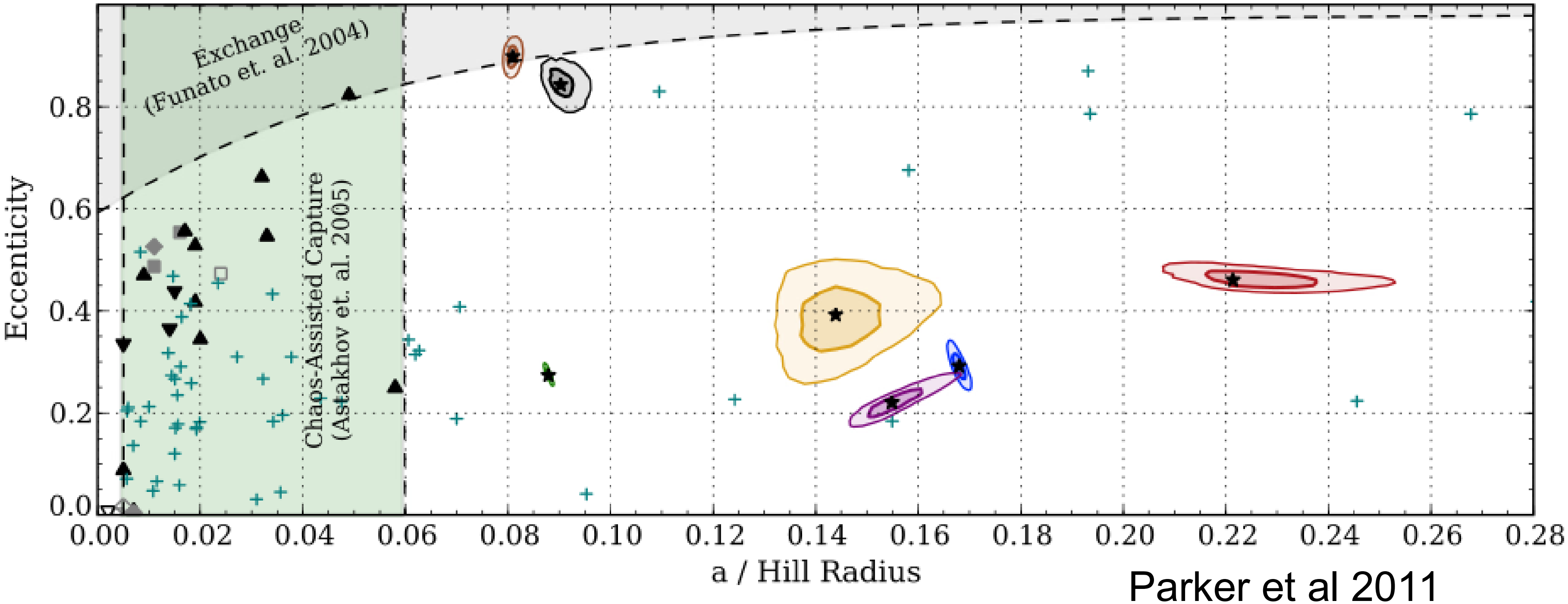


Yang et al 2016, Carrera et al 2015

Signs of Planetesimal Formation by Gravitational Instability

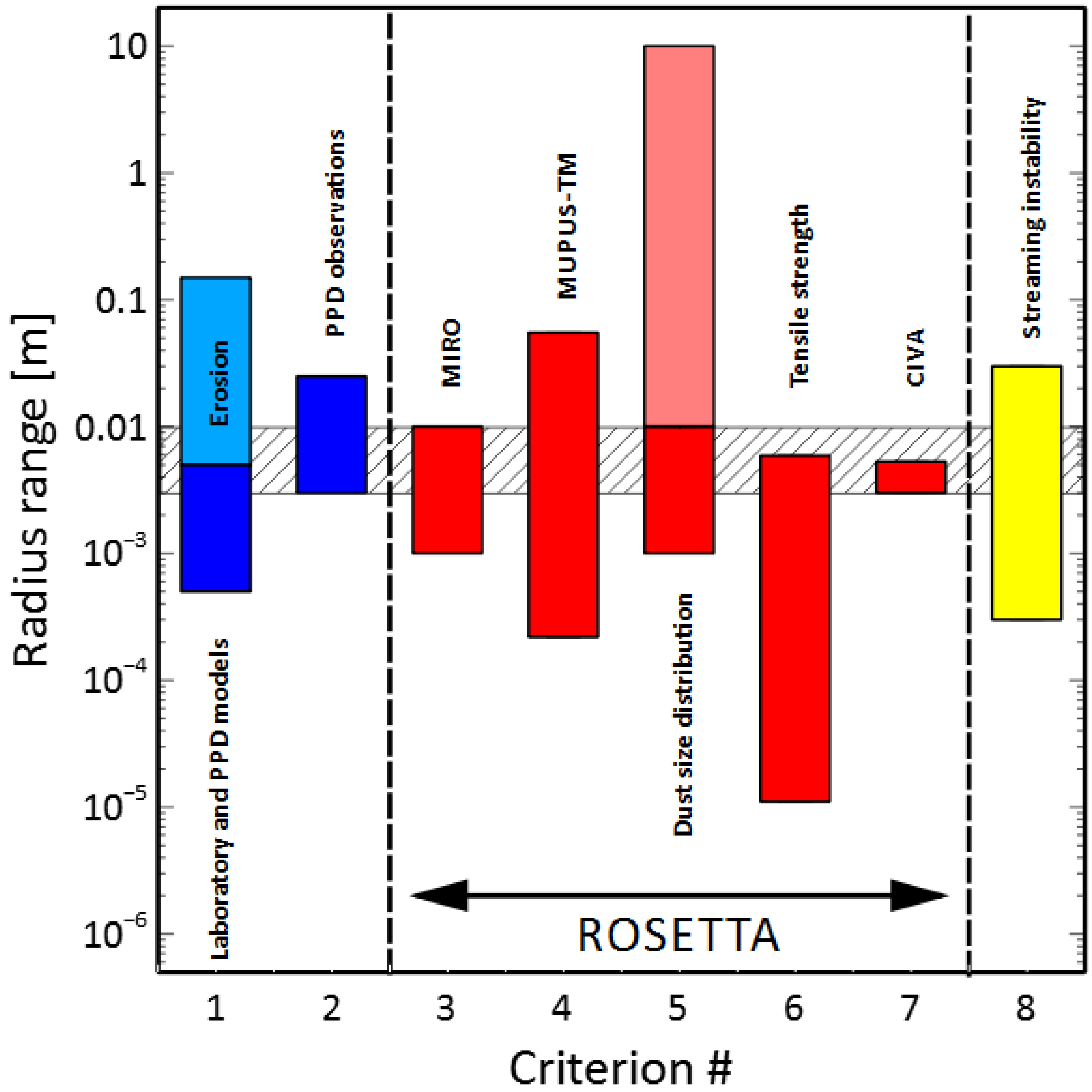


Nesvorny, Youdin, Richardson (2010)



Parker et al 2011

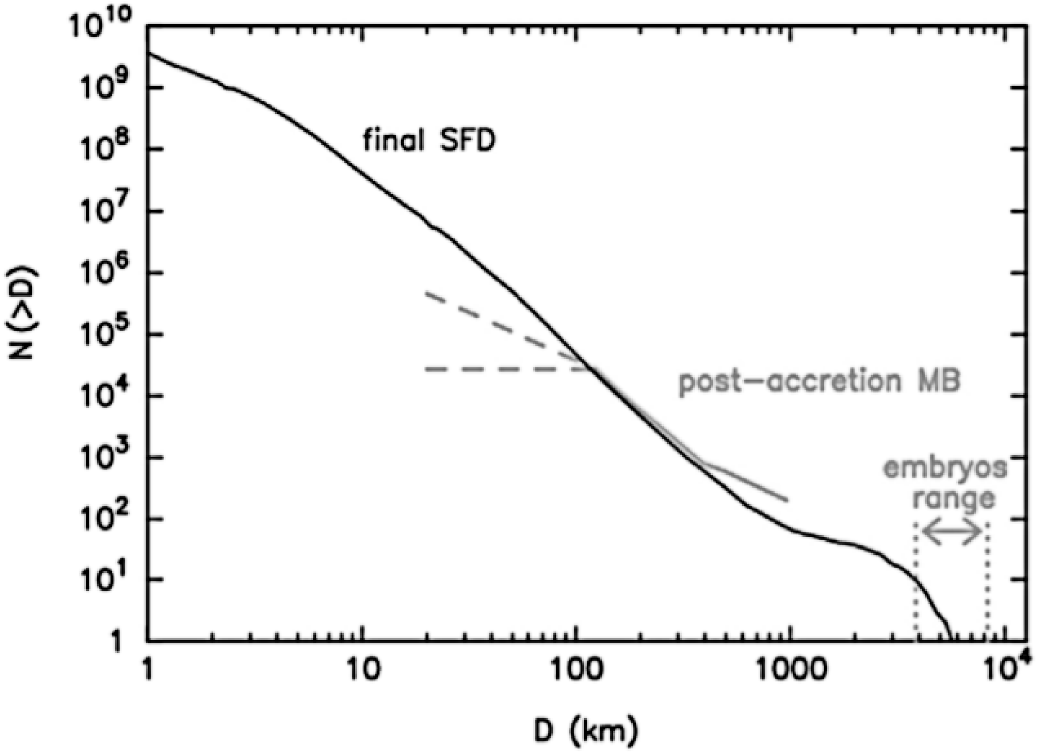
Signs of Pebbles in Comet C-G from Rosetta



- MIRO: areal diurnal temperature variations
- MUPUS-TM: local diurnal temperature variations
- Dust-size distributions derived from Rosetta observations by COSIMA, GIADA, OSIRIS and from the ground.
- Tensile-strength values derived from various *Rosetta* observations correspond to dust-aggregate sizes according to Skorov & Blum 2012 model.
- CIVA: direct imaging of dust “pebbles” from *Philae*.

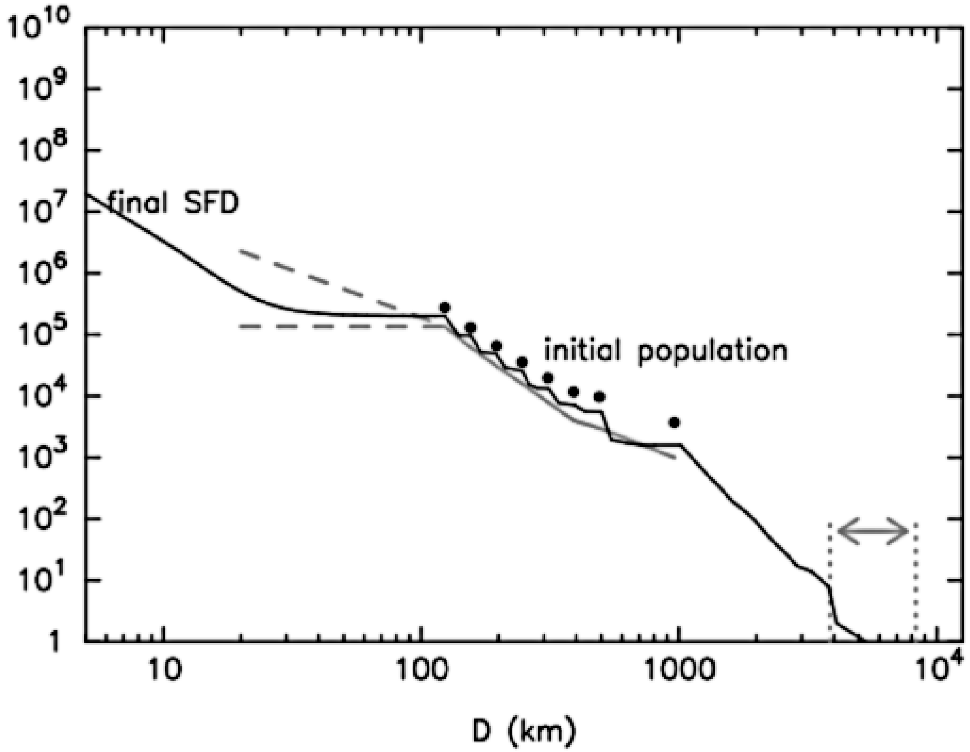
Blum et al. (subm. to MNRAS) slide courtesy of Jürgen Blum

Signs of Planetesimal Formation by Gravitational Instability



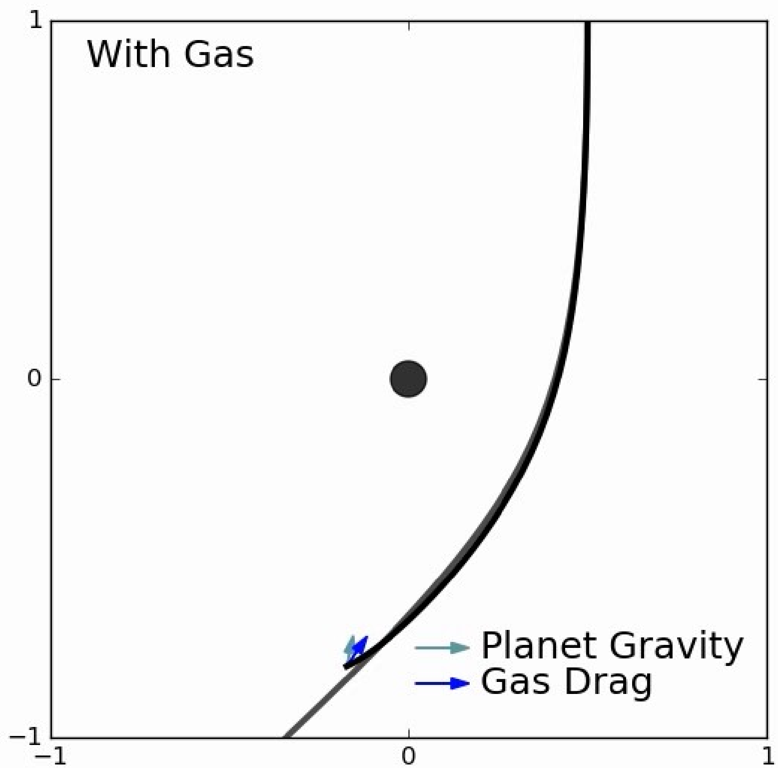
Starting from 10 km planetesimals

Starting from 100-1000 km planetesimals

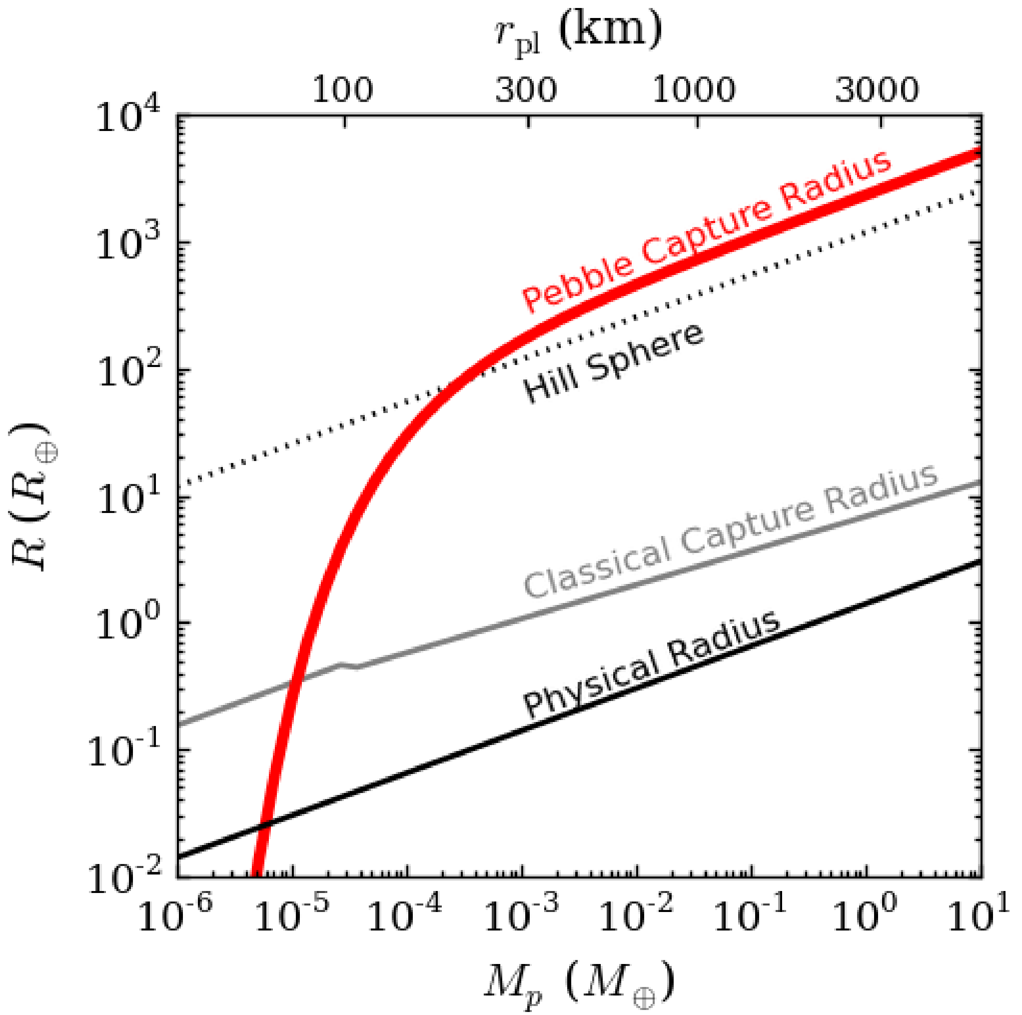


Morbidelli et al 2009

Pebbles + Planetesimals = Pebble Accretion



Lambrechts & Johansen (2012)

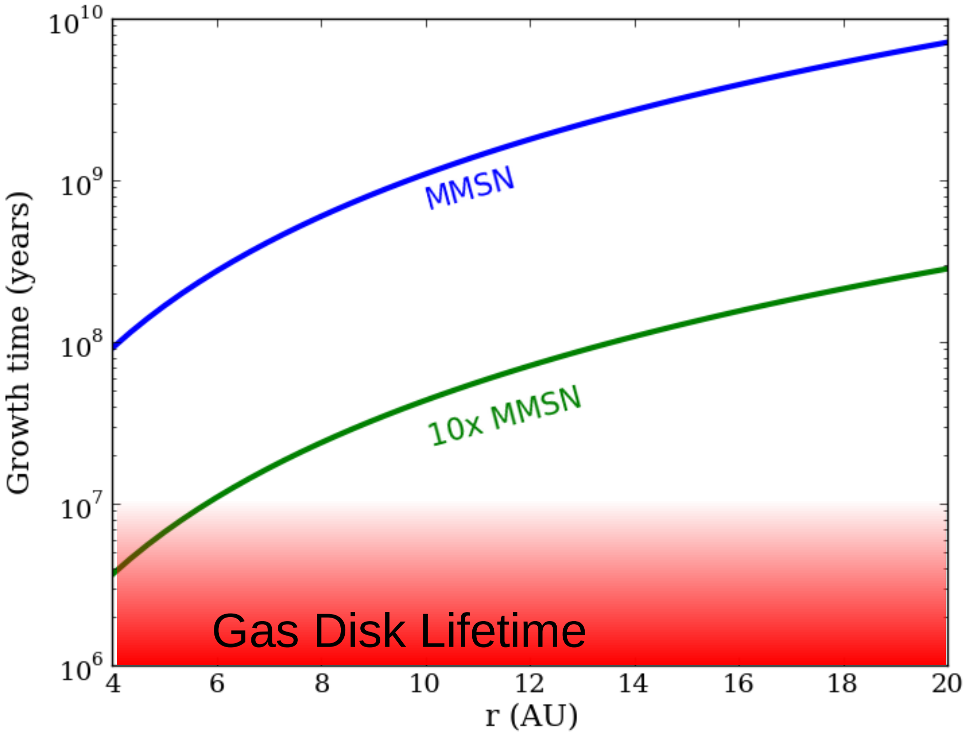


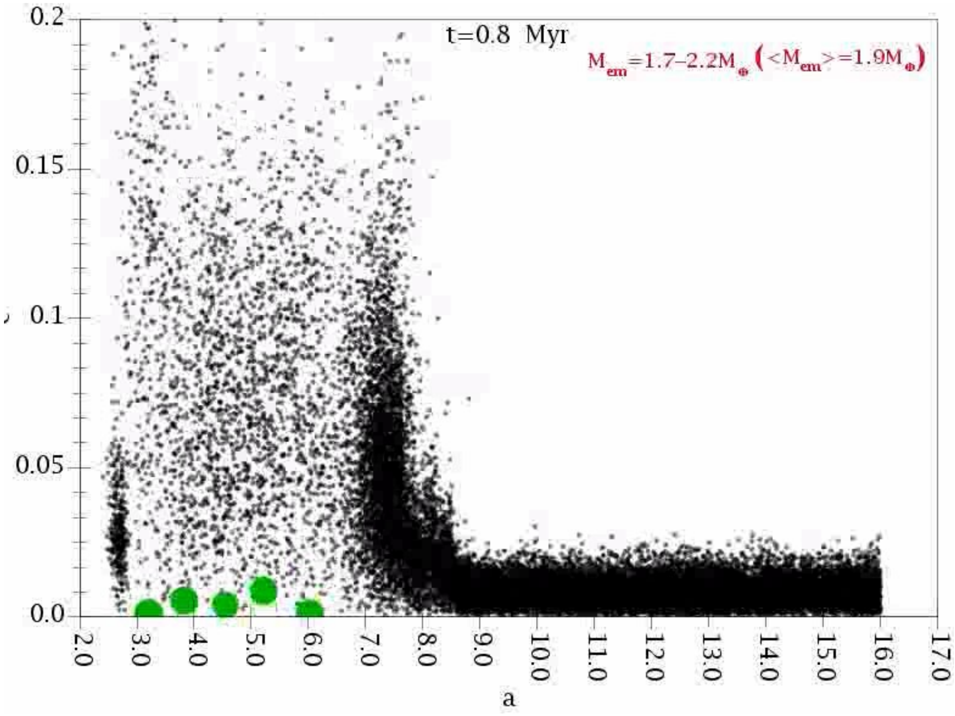
Curves from Ormel & Klahr (2010) and Ravikov (2004)

Solves a problem in Giant Planet Core Formation!

Large planetesimals = too slow of formation

Small planetesimals = gaps not growth





e.g. Thommes & Duncan 2006

Levison et al 2010

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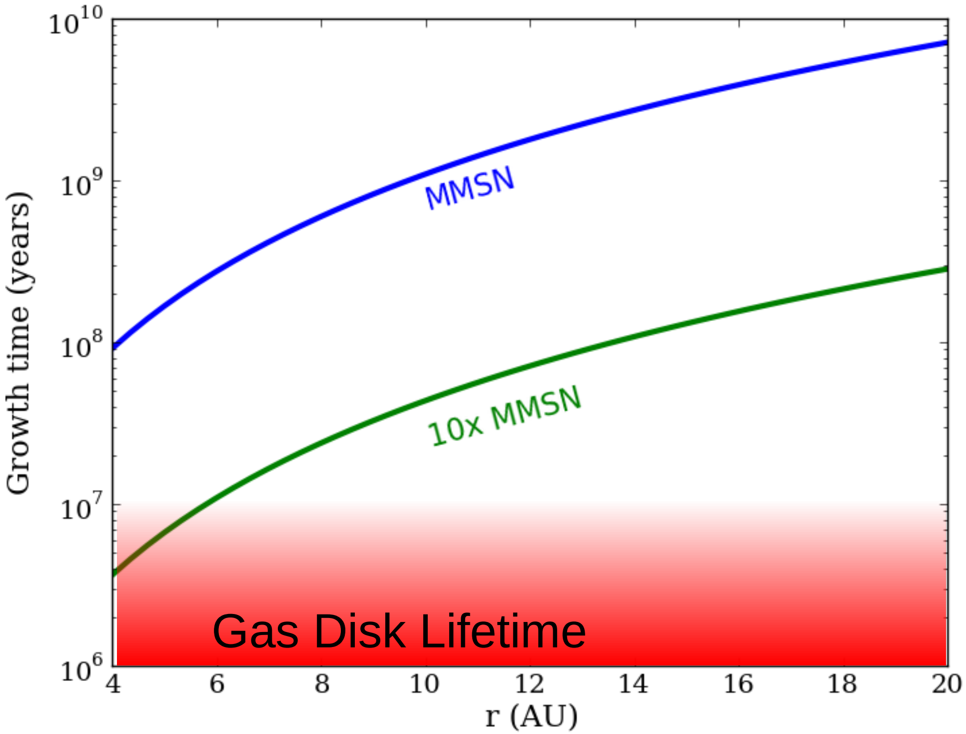
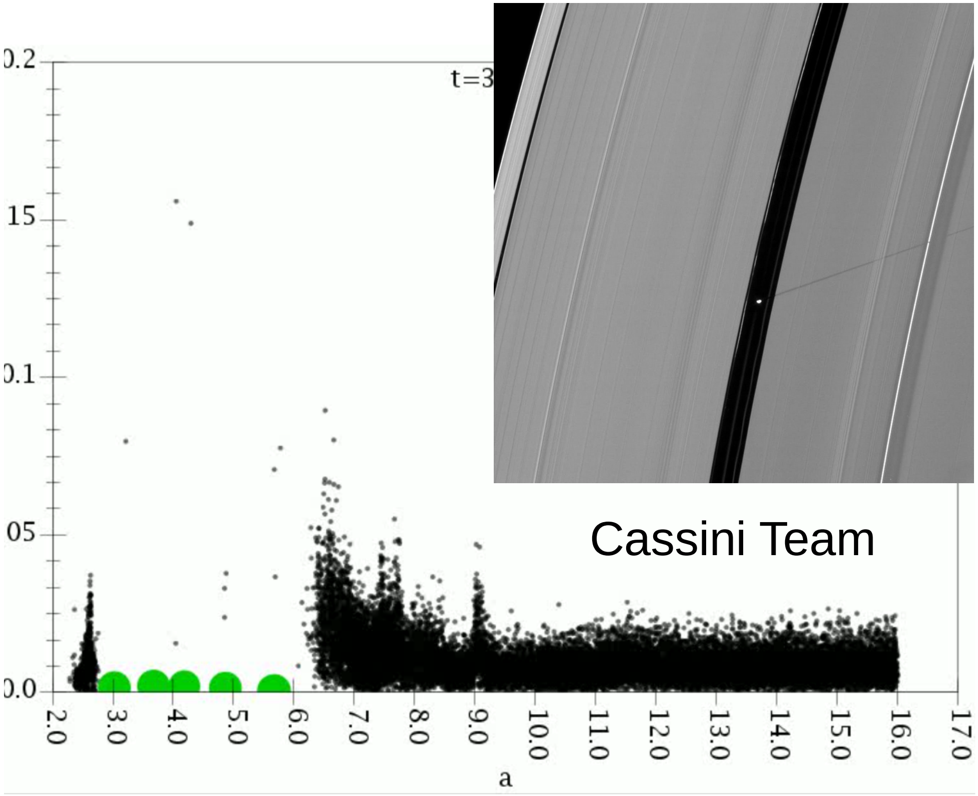
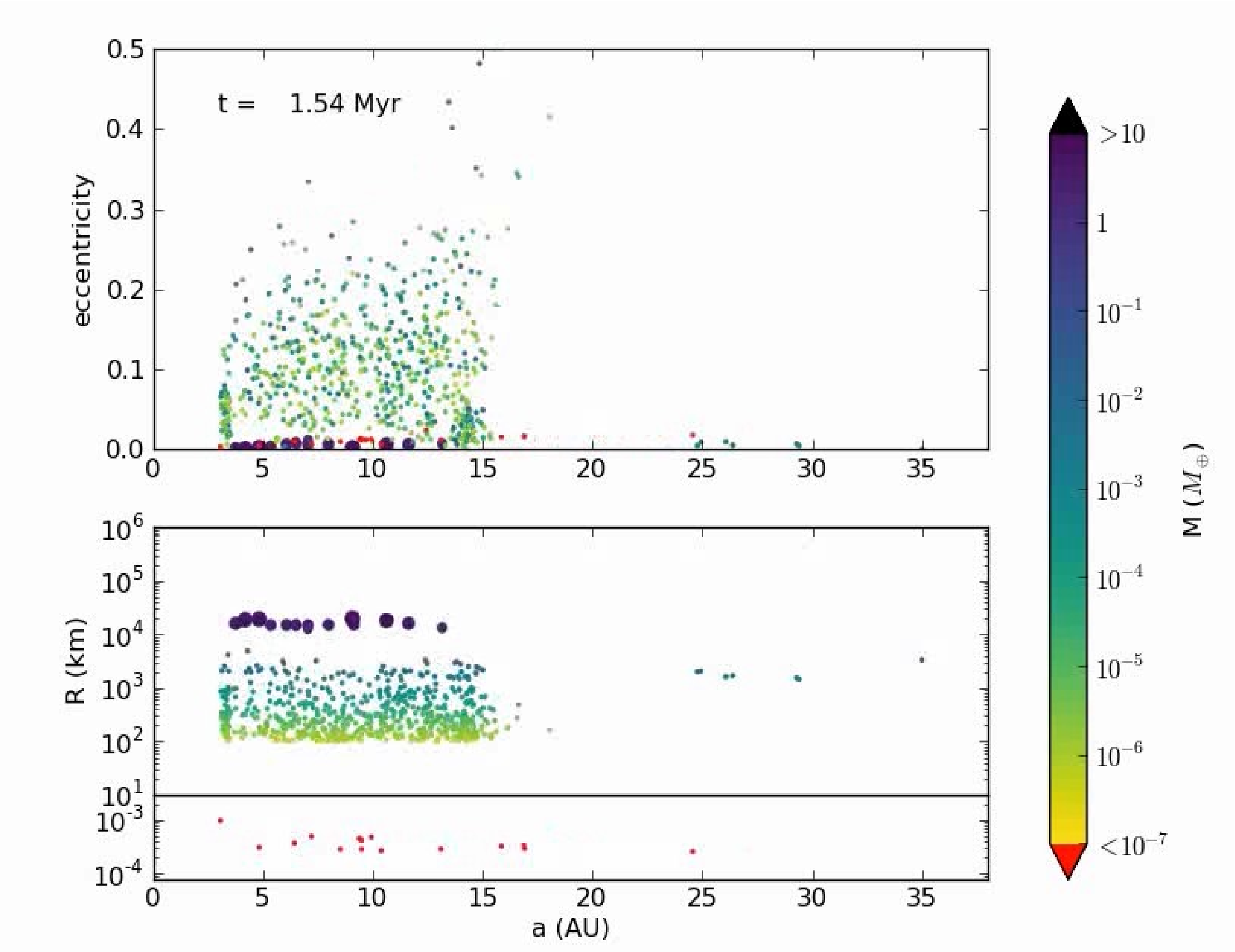


e.g. Thommes & Duncan 2006



Levison et al 2010

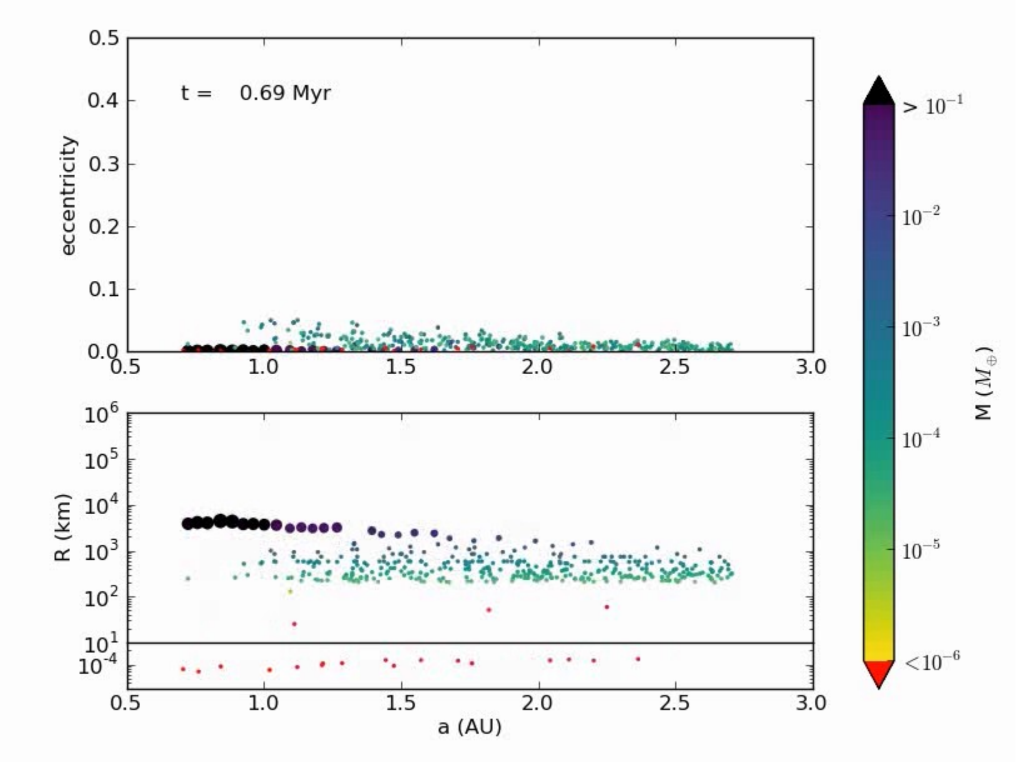
Pebbles can form Giant Planet Cores



Levison, Kretke & Duncan (2015)

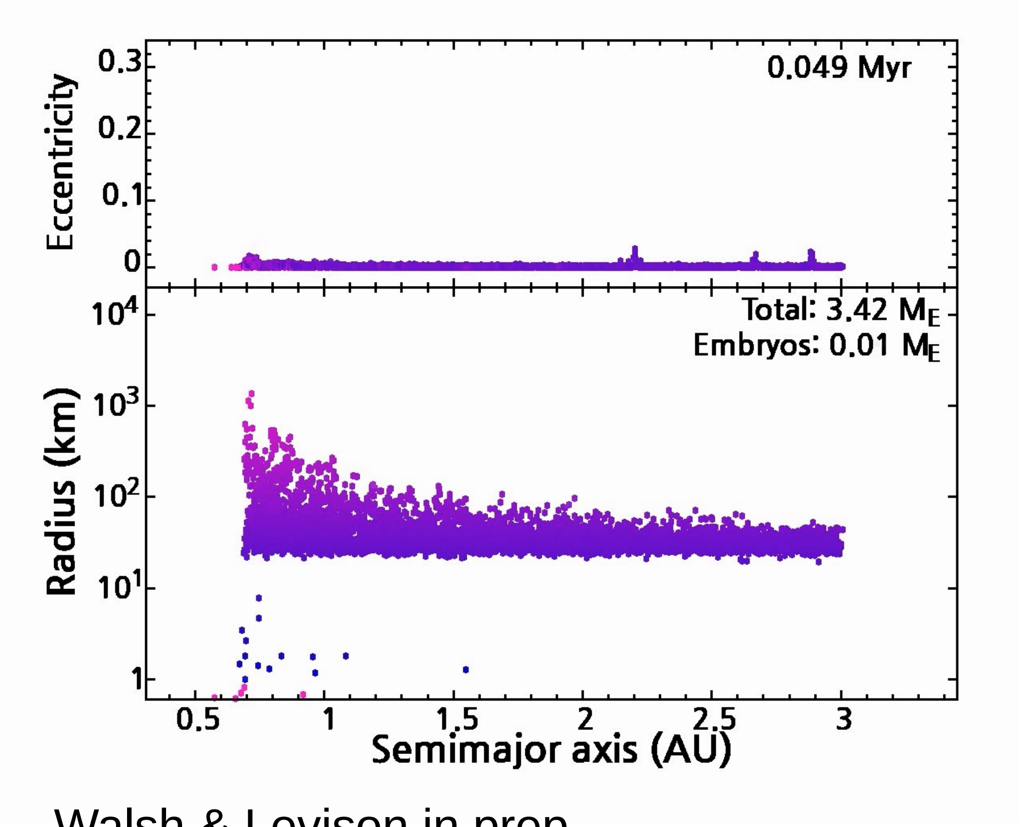
Less clear in the terrestrial planet region

Pebble Accretion



Levison, Kretke et al 2015

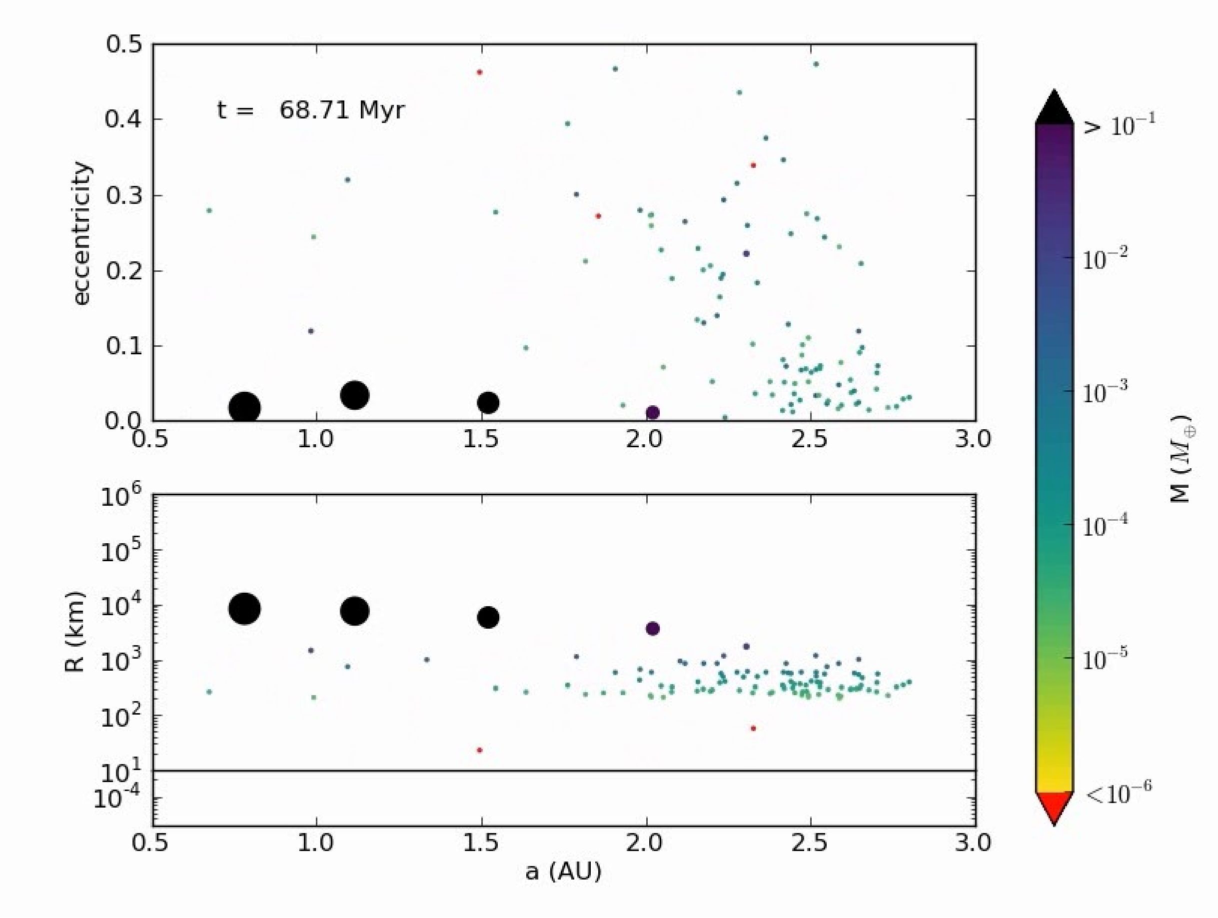
Planetesimal Accretion



Walsh & Levison in prep

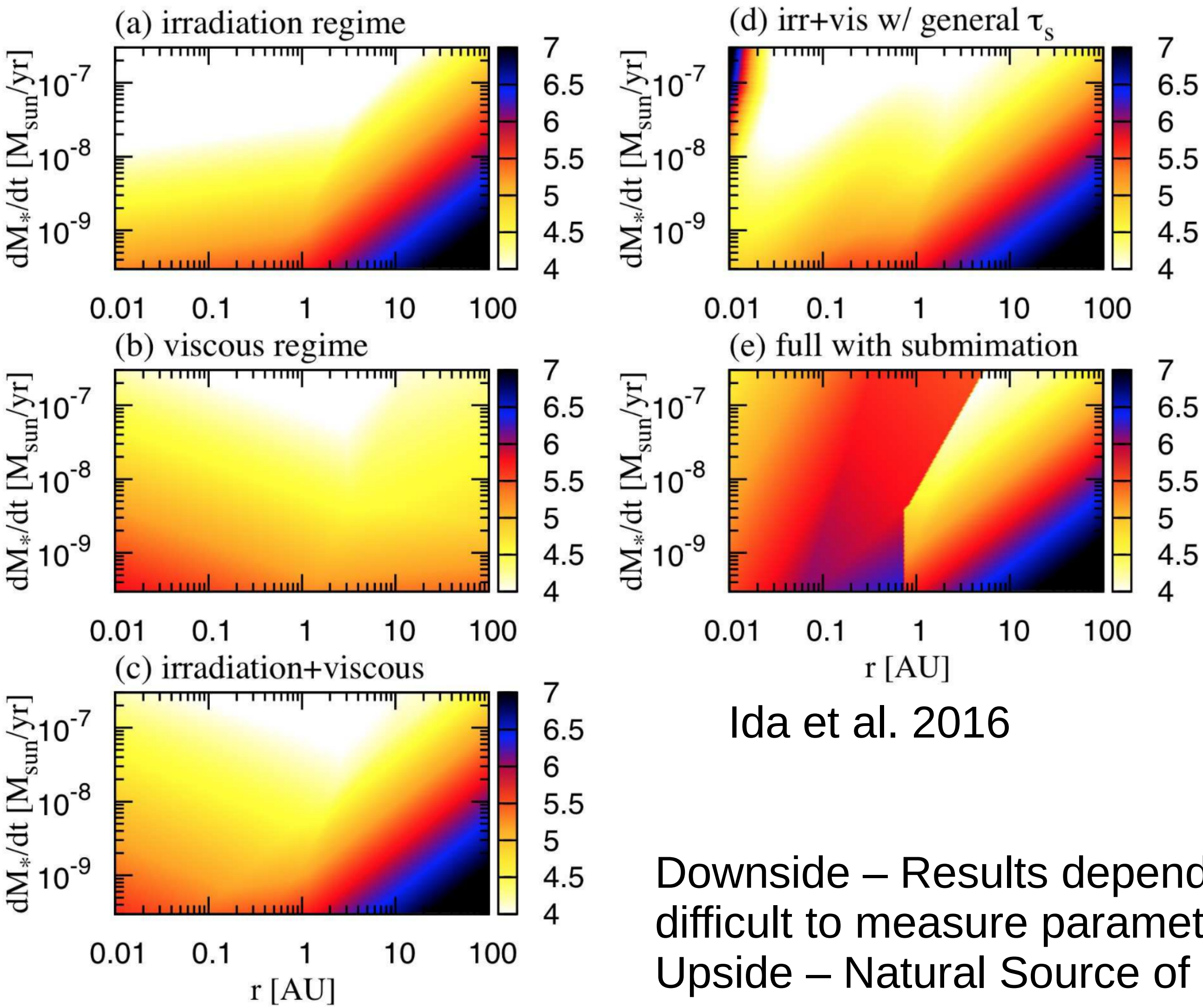
Mass limited by: Pebble Flux v. Initial surface density of planetesimals

Either way, the final stage of terrestrial planet formation similar



Levison, Kretke et al 2015

Depends on size of planetesimals, pebbles, and disk structure



Different Assumptions of Disk Structure

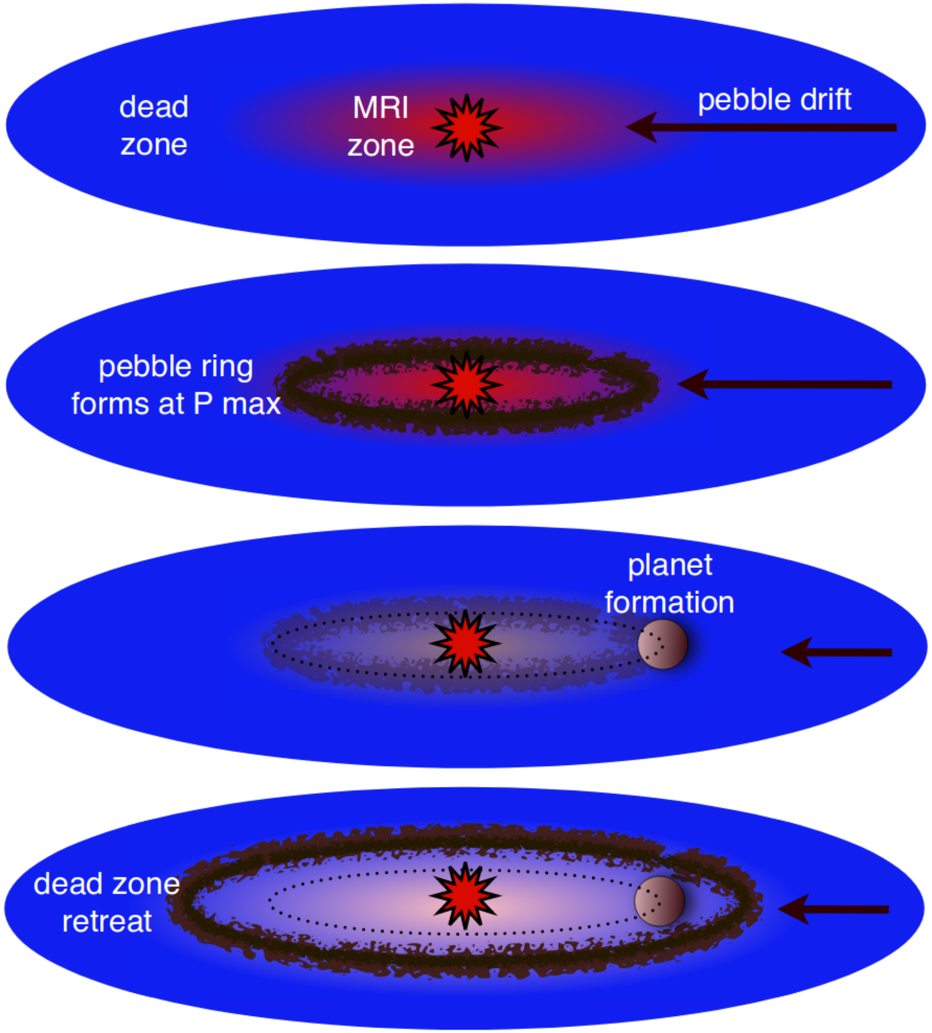
Shorter Formation Times

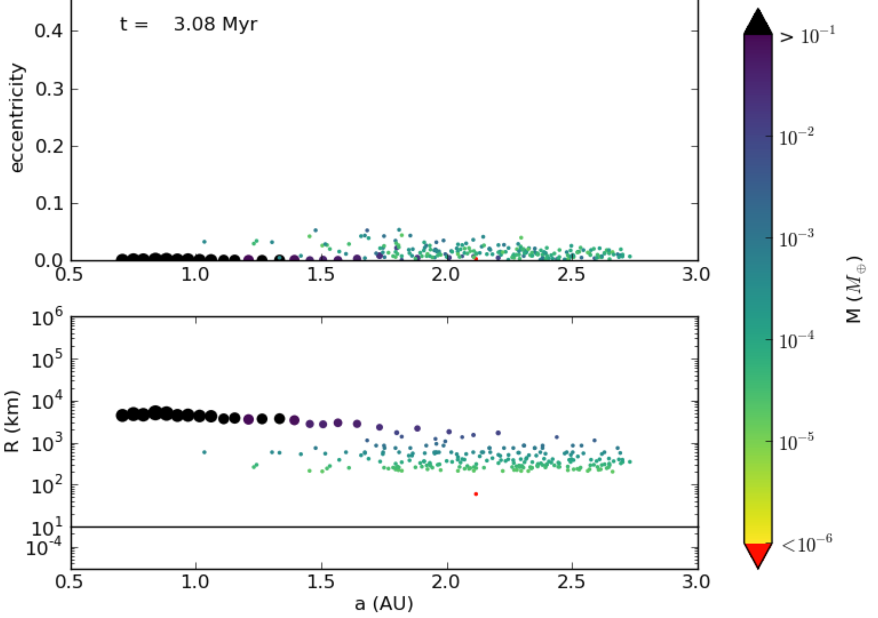
Different Assumption of Pebble Properties

Ida et al. 2016

Downside – Results depend sensitively on difficult to measure parameters
Upside – Natural Source of Exoplanet Variability!

A source of short period planets?

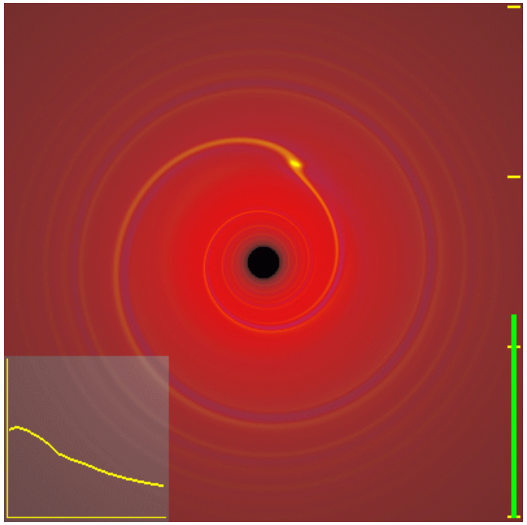




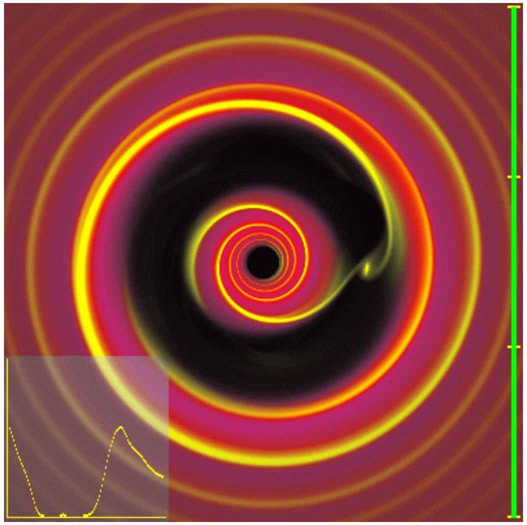
Chatterjee & Tan (2014)

Or… You can just move the planets

Type I – low mass planets

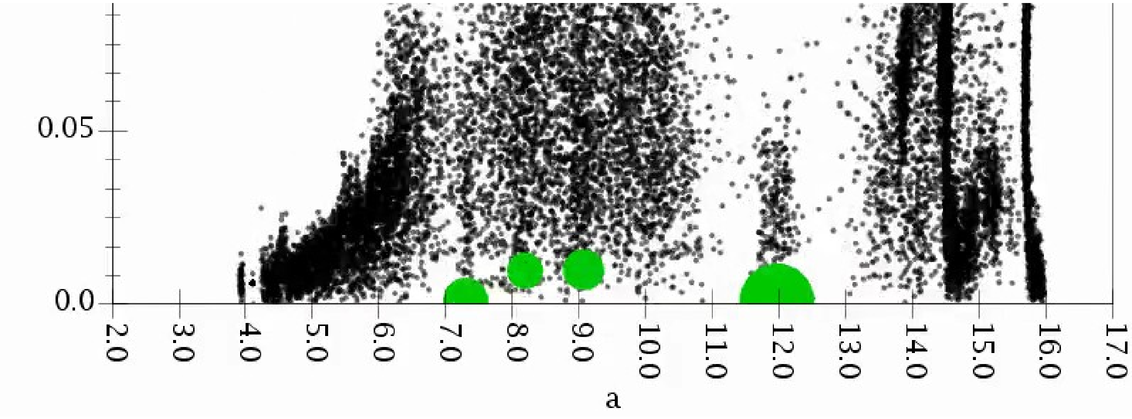


Type II – high mass planets



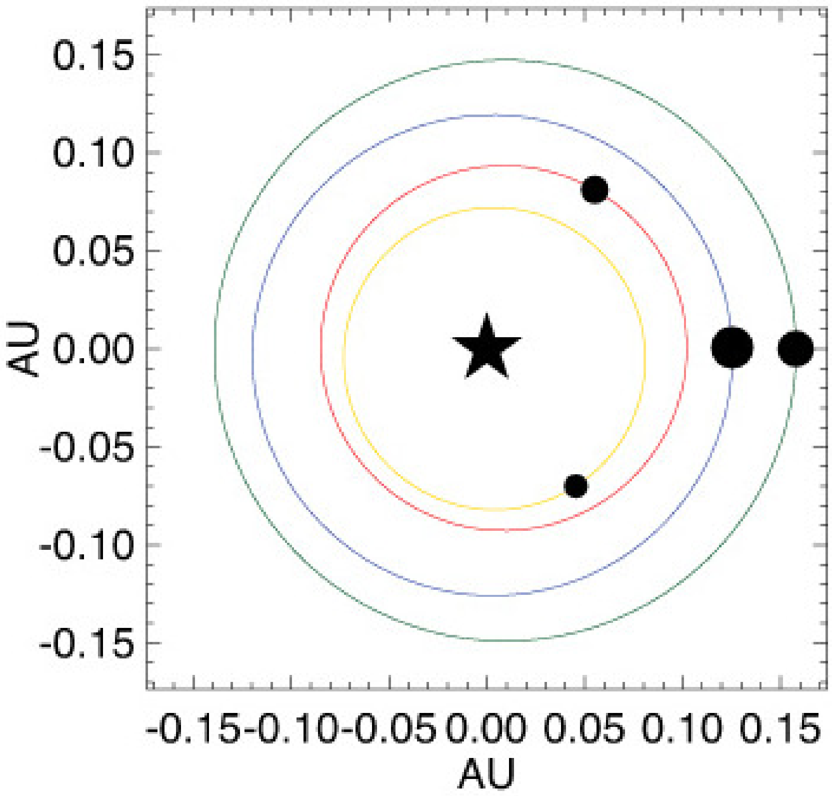
e.g. Armitage & Rice (2005)

e.g. Minton & Levison (2012)

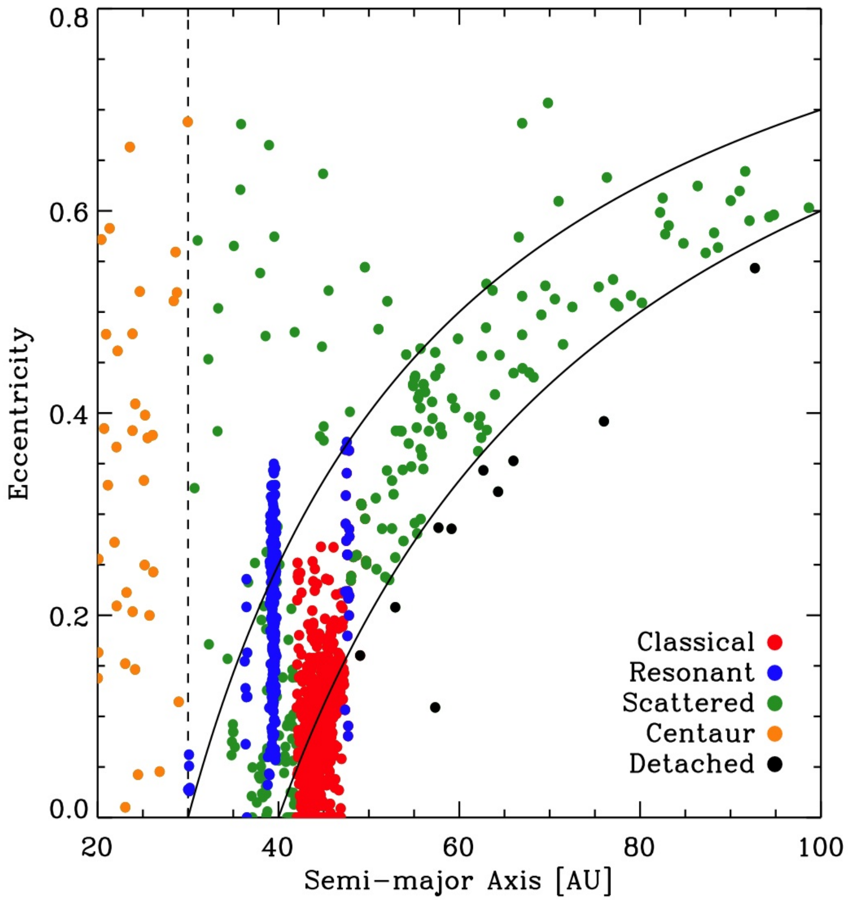


Evidence for Migration

Kepler 223

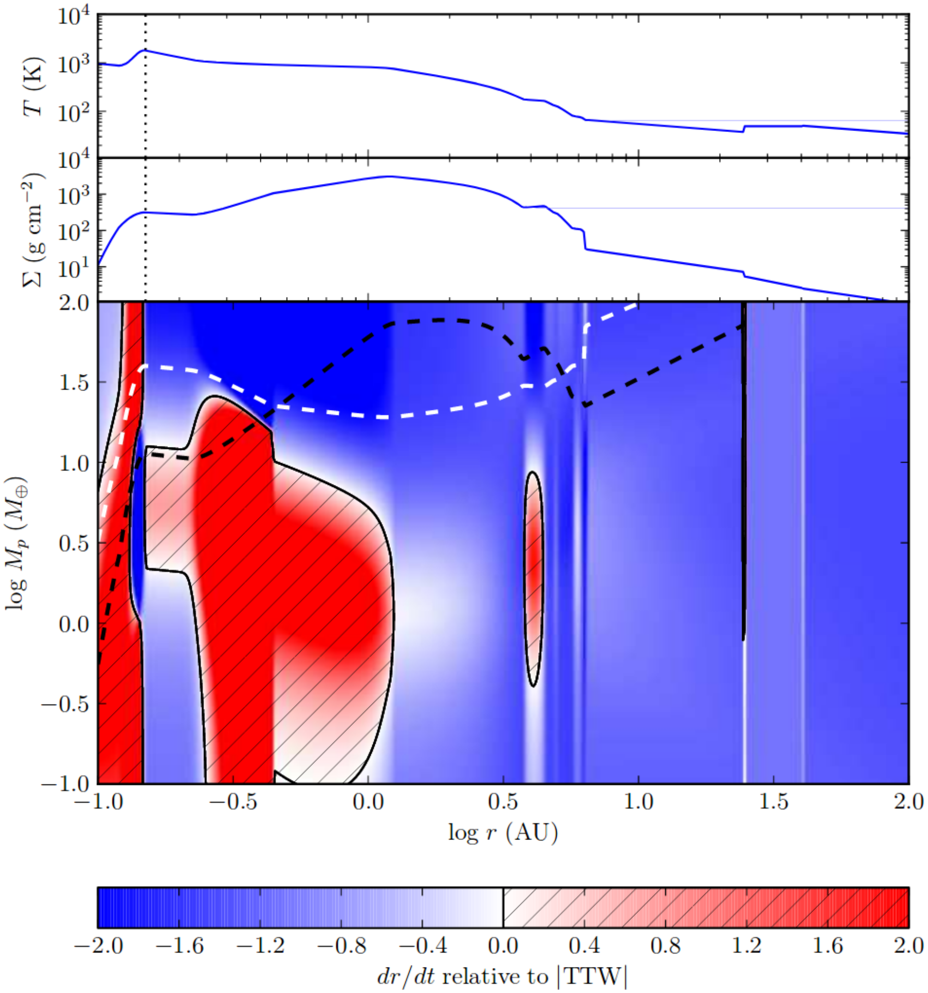


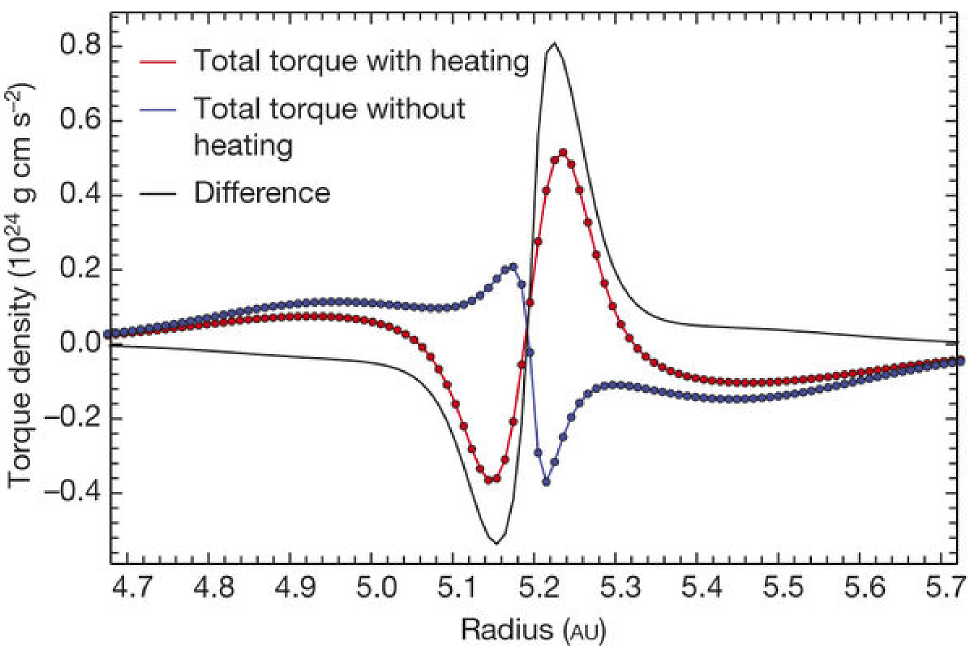
Our Solar System



Mills et al 2016

Direction of Type I migration

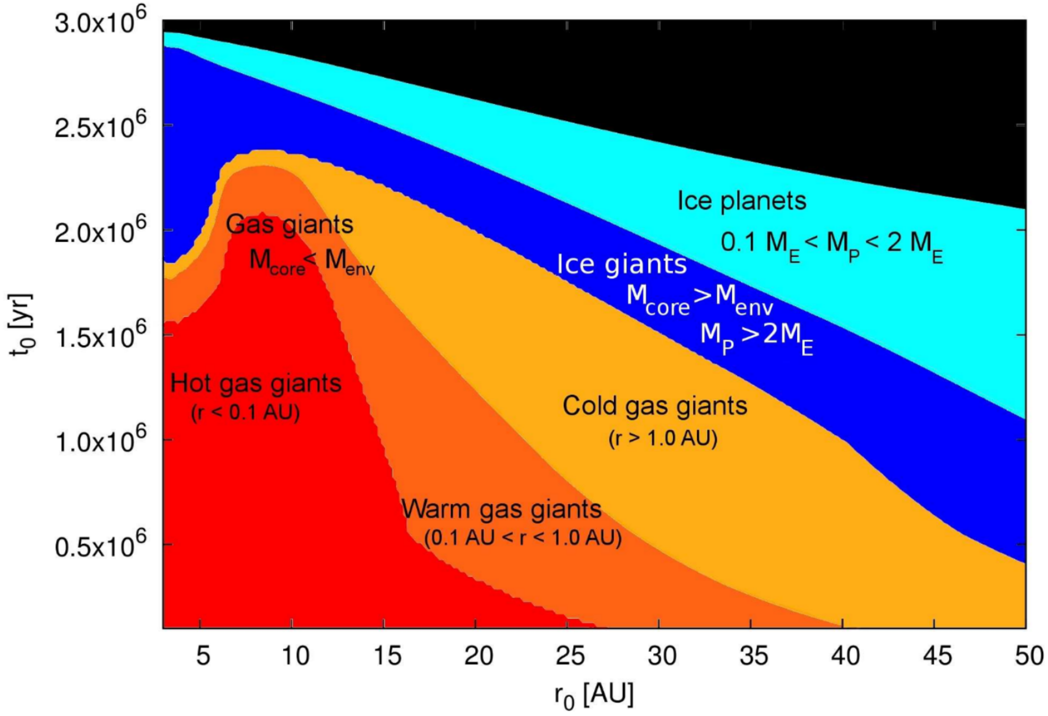




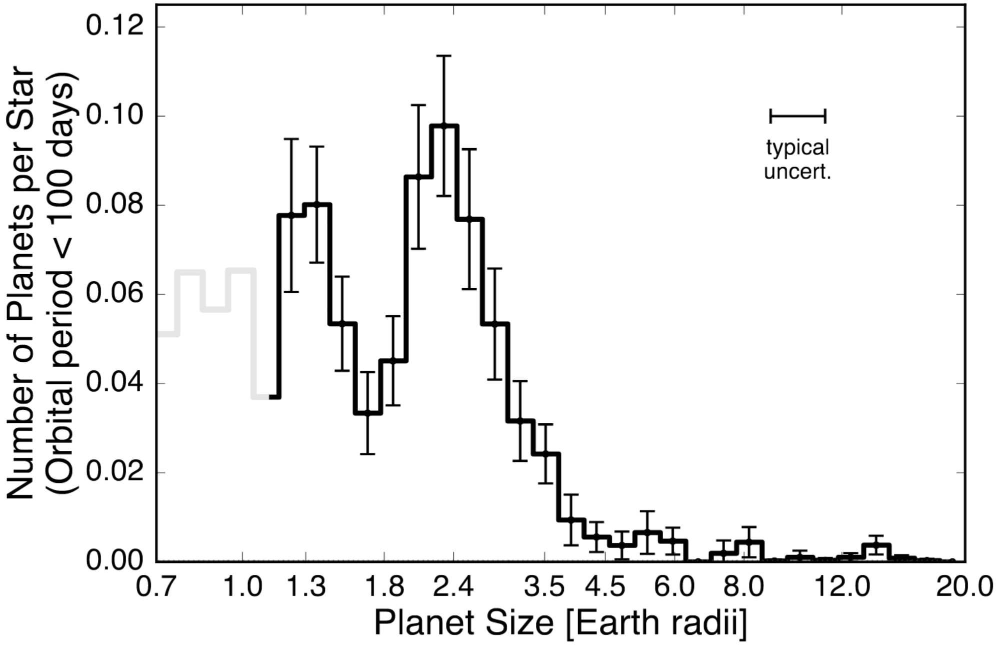
Benitez-Llambay et al 2015

Paardekooper et al 2010 e.g. Kretke & Lin 2012

Type I Migration still a problem



Bitsch et al 2015

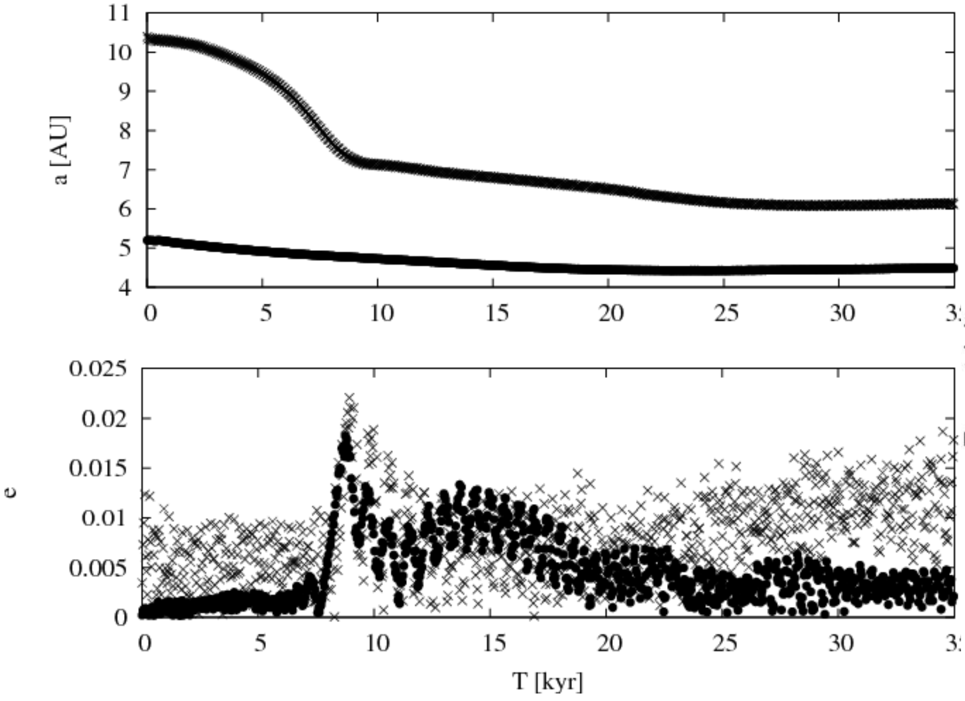


Fulton et al 2017

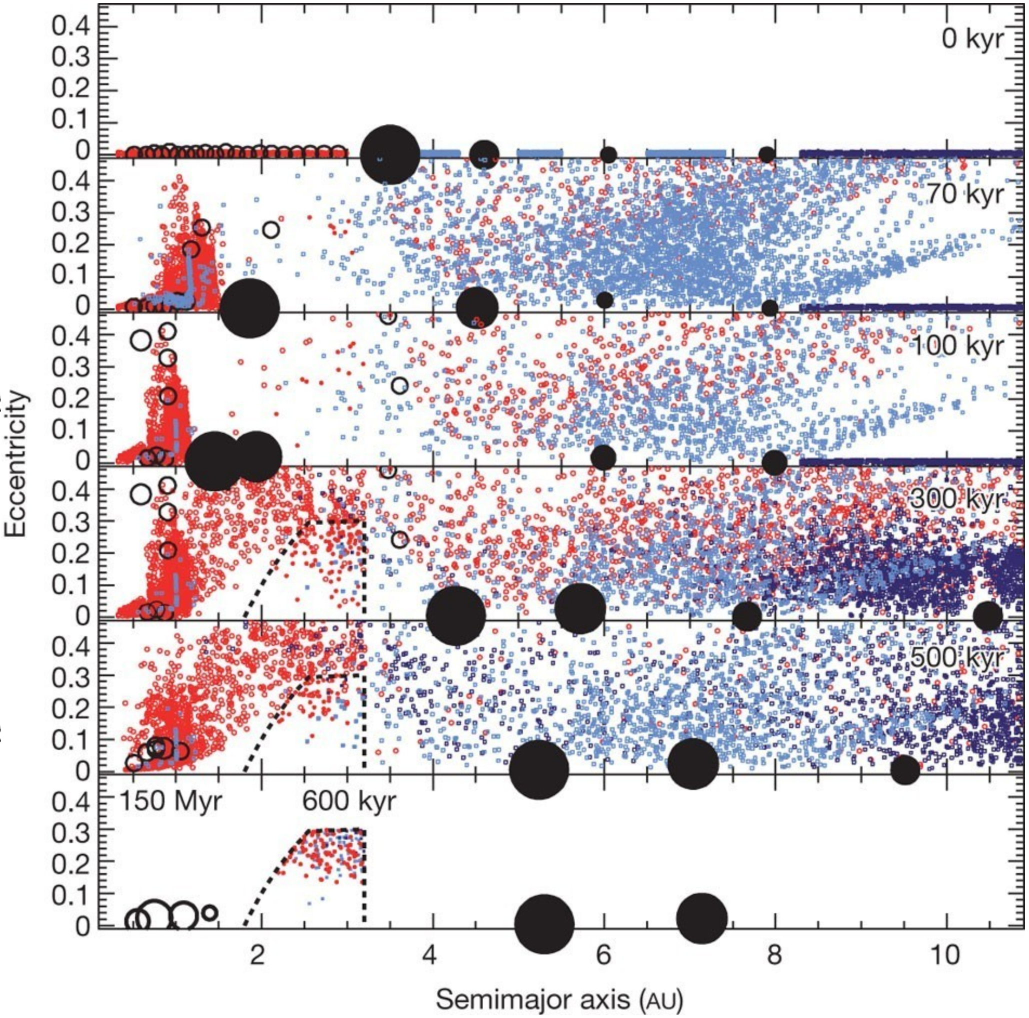
Even with pebble accretion, icy planets are predicted to migrate substantially

Short period super Earths appear rocky

Type II migration in our Solar System?

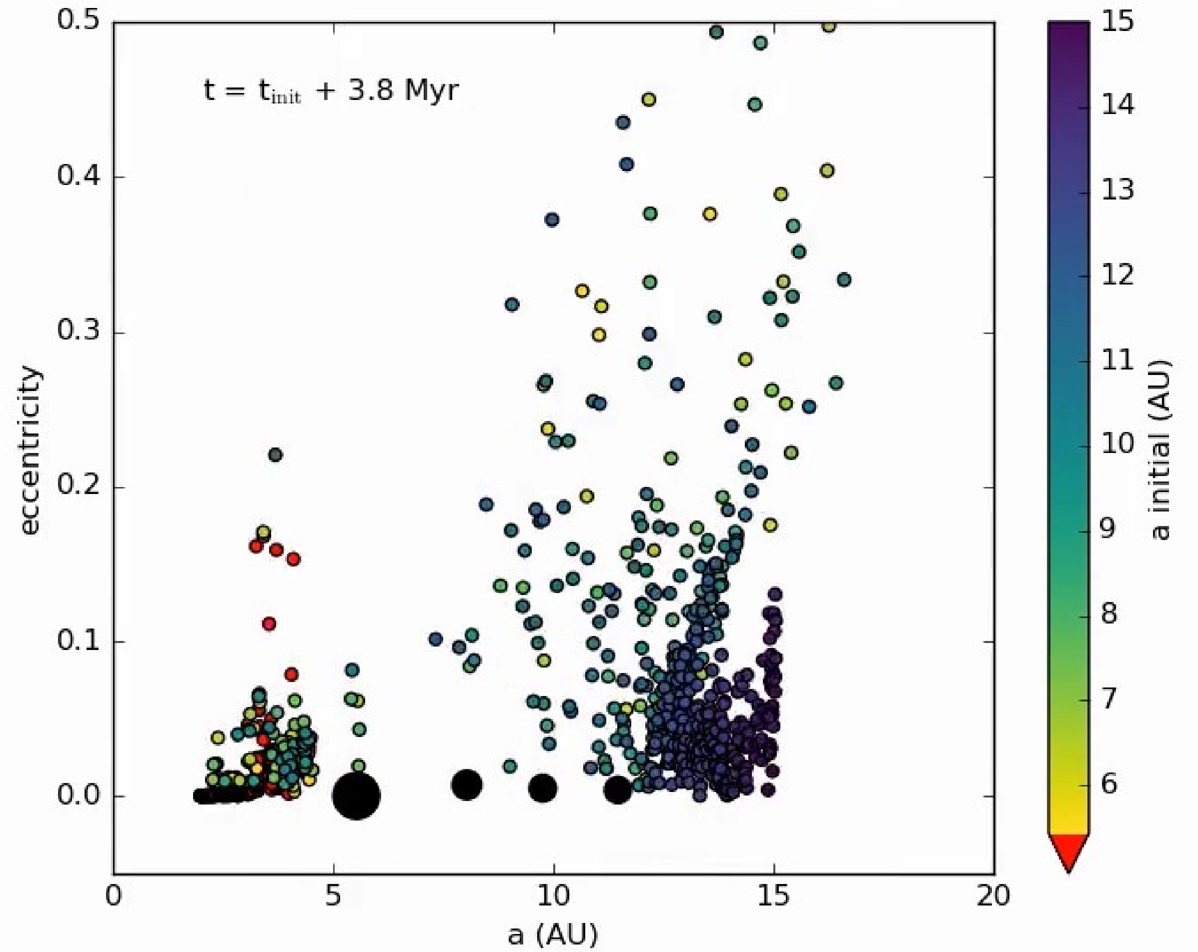


Masset & Snellgrove (2007)
e.g. Morbidelli & Crida (2007)



Walsh et al 2011,2012

Giant planet formation scatters planetesimals



e.g. Kretke et al in prep, Raymond & Izidoro 2017

Conclusions

- Growth to ~mm to cm sized particles should be relatively efficient, but then growth stalls
- These "pebbles" can be collected to form planetesimals, and later accreted to form planets
  - This likely implies wide scale mixing of small particles, is this consistent with constraints?
- The mass of proto-terrestrial planets (while the gas is around) is limited either by the initial planetesimals or the pebble flux
- Planet migration clearly happens sometimes, but it doesn't appear to always happen