Formation and Discovery of

Extrasolar Planetary Systems

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Formation and Discovery of

Extrasolar Planetary Systems

Physical principles of planet formation

orbital stability + encounter outcomes

Giant exoplanets

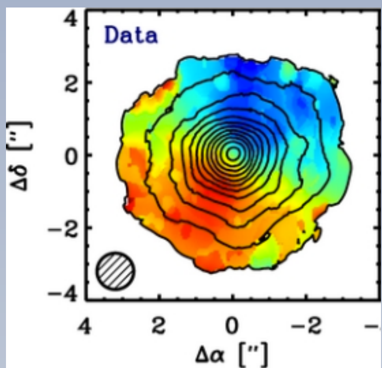
dynamical evolution, migration

Terrestrial exoplanets

coupling to giants, Kepler

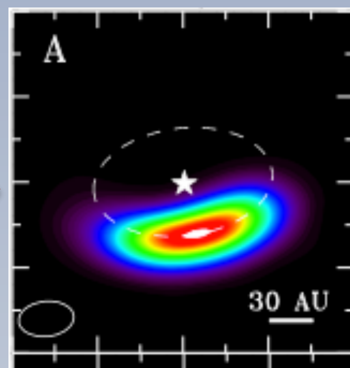
What can we observe?

protoplanetary
disks



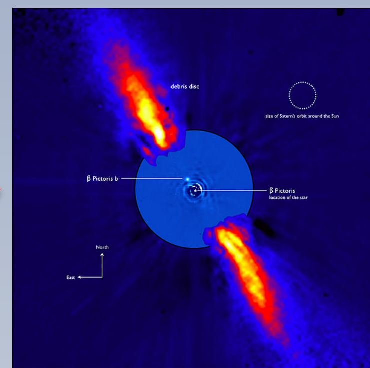
Gas
Dust s ~ 1mm

transition
disks



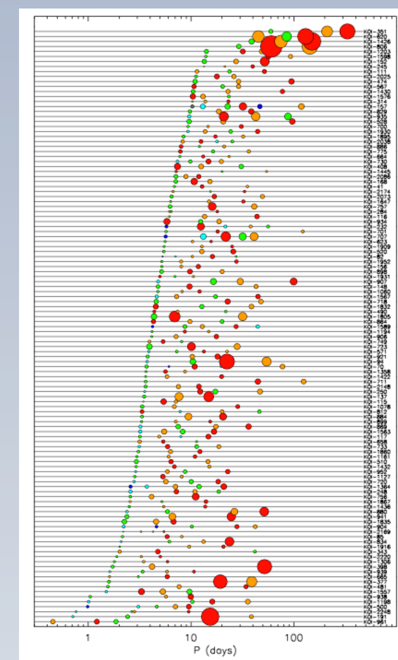
Gas – dust
interaction

debris
disks



Dust from
collisions

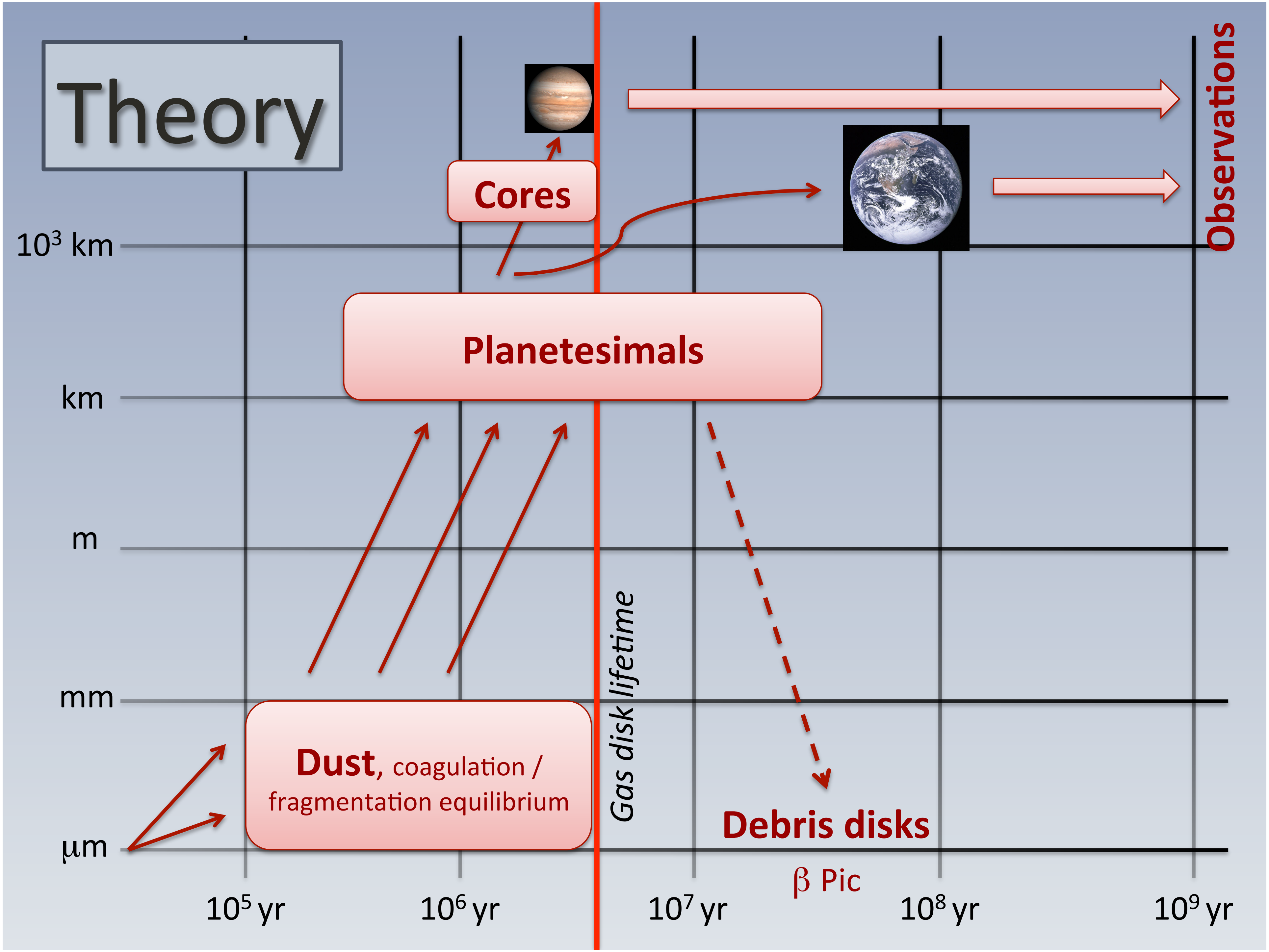
planets



N-body
dynamics

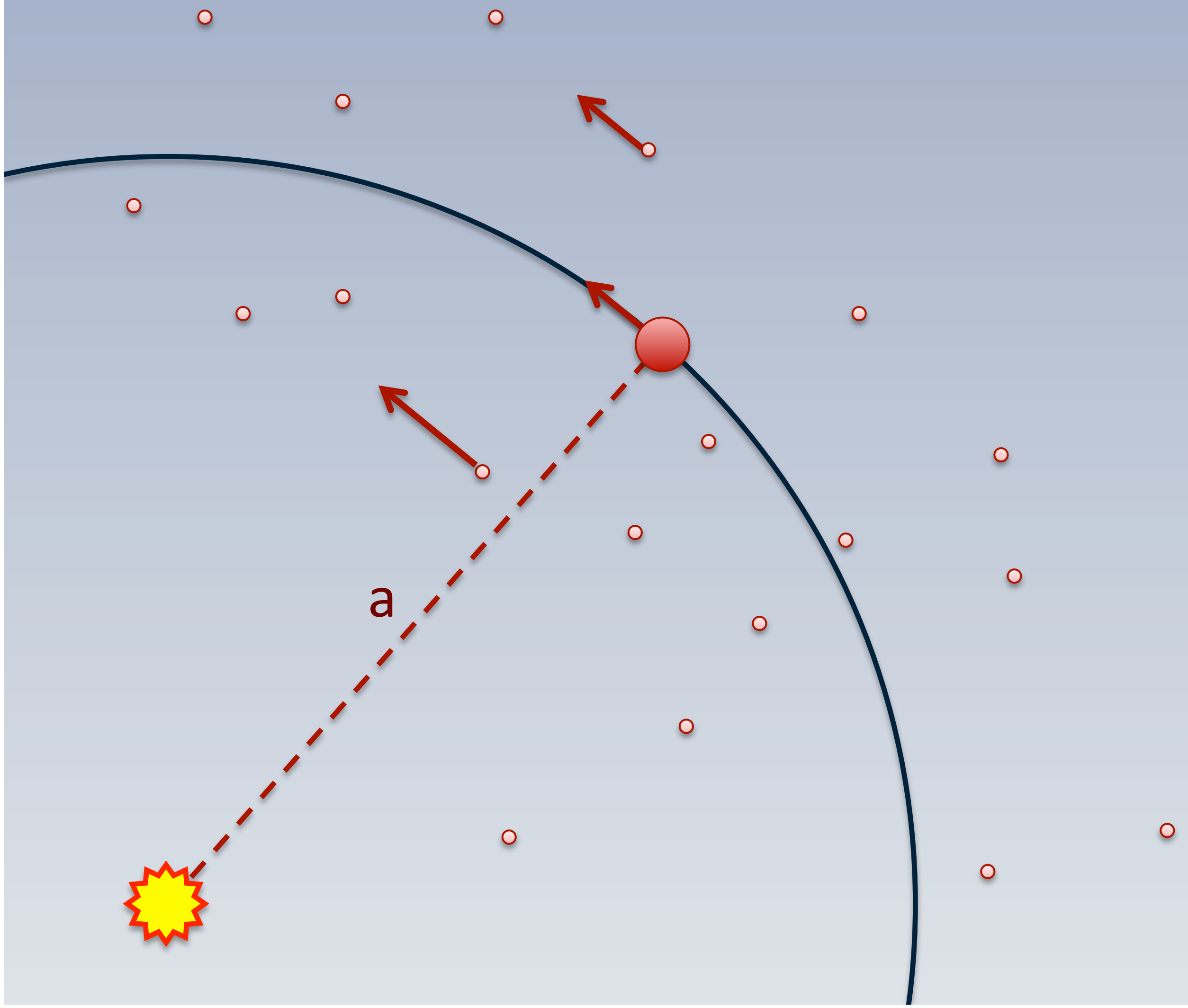
Missing:

- growth mm – km ("planetesimals")
- planet-gas disk interactions
- young planetary systems



Theory
Observations
Cores
Planetesimals
Dust, coagulation / fragmentation equilibrium
Gas disk lifetime
Debris disks
β Pic
10³ km
km
m
mm
μm
10⁵ yr
10⁶ yr
10⁷ yr
10⁸ yr
10⁹ yr

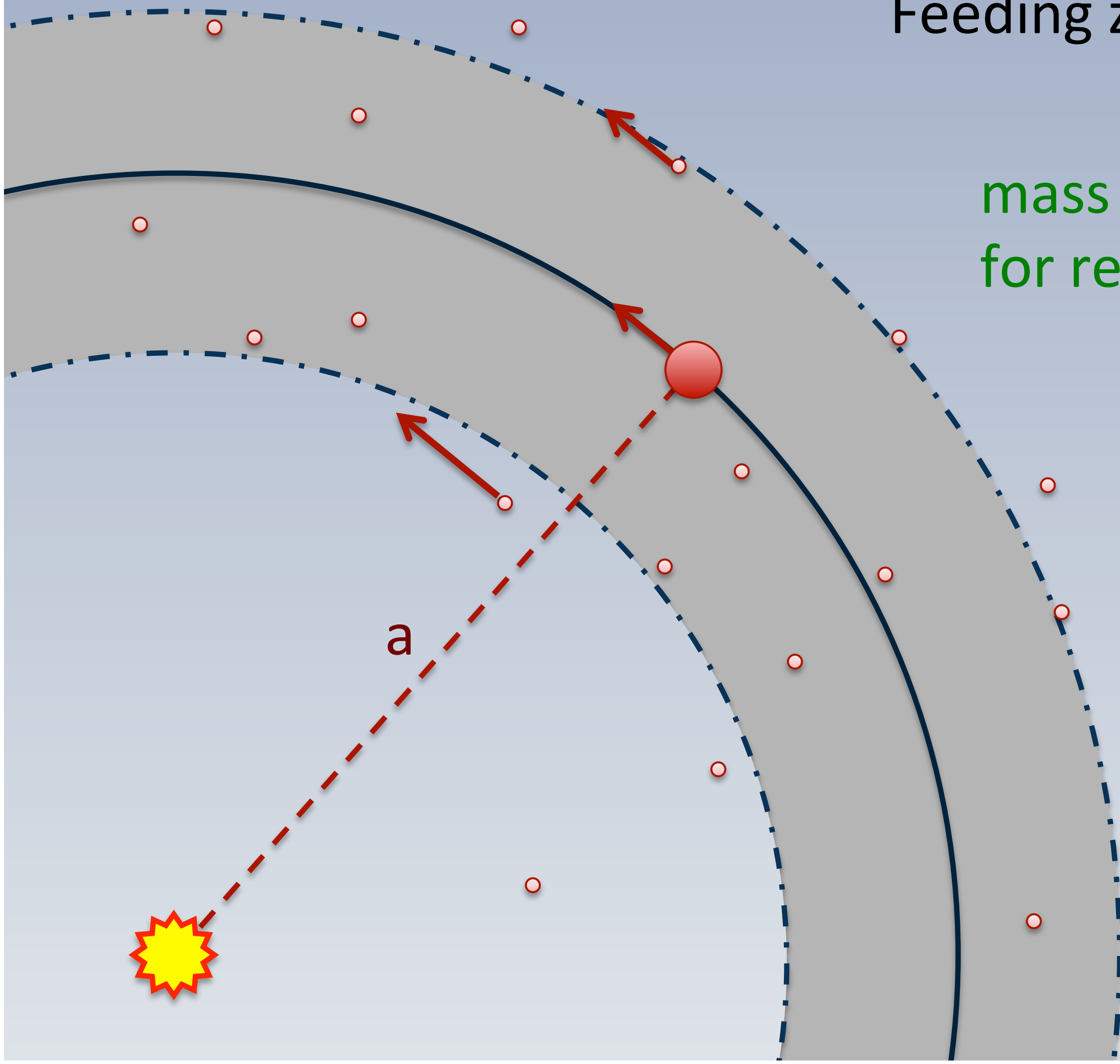
Dynamics of growth



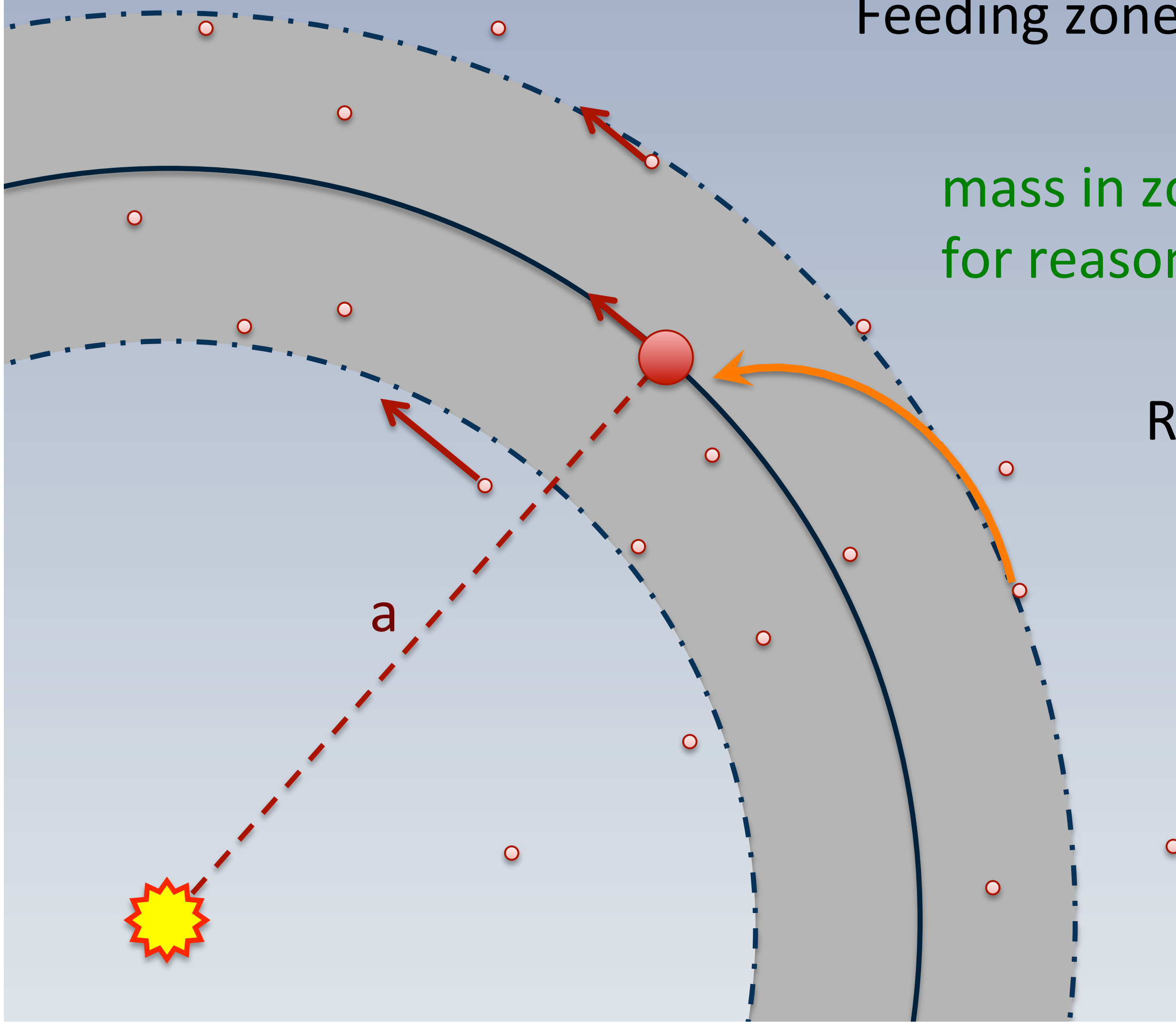
Dynamics of growth

Feeding zone: $$\Delta a = C\left(\frac{M_p}{3M_*}\right)^{1/3} a$$

mass in zone $4\pi a \Delta a \Sigma$ increases
for reasonable $\Sigma(r)$, m ~ a



Dynamics of growth



Feeding zone: $$\Delta a = C\left(\frac{M_p}{3M_*}\right)^{1/3} a$$

mass in zone $4\pi a\Delta a\Sigma$ increases for reasonable $\Sigma(r)$, m ~ a

Ratio: $$\frac{v_{esc}}{v_K} \propto \sqrt{\frac{M_p}{M_*}\frac{a}{R_p}}$$

if large, scattering or ejection

if small, collision

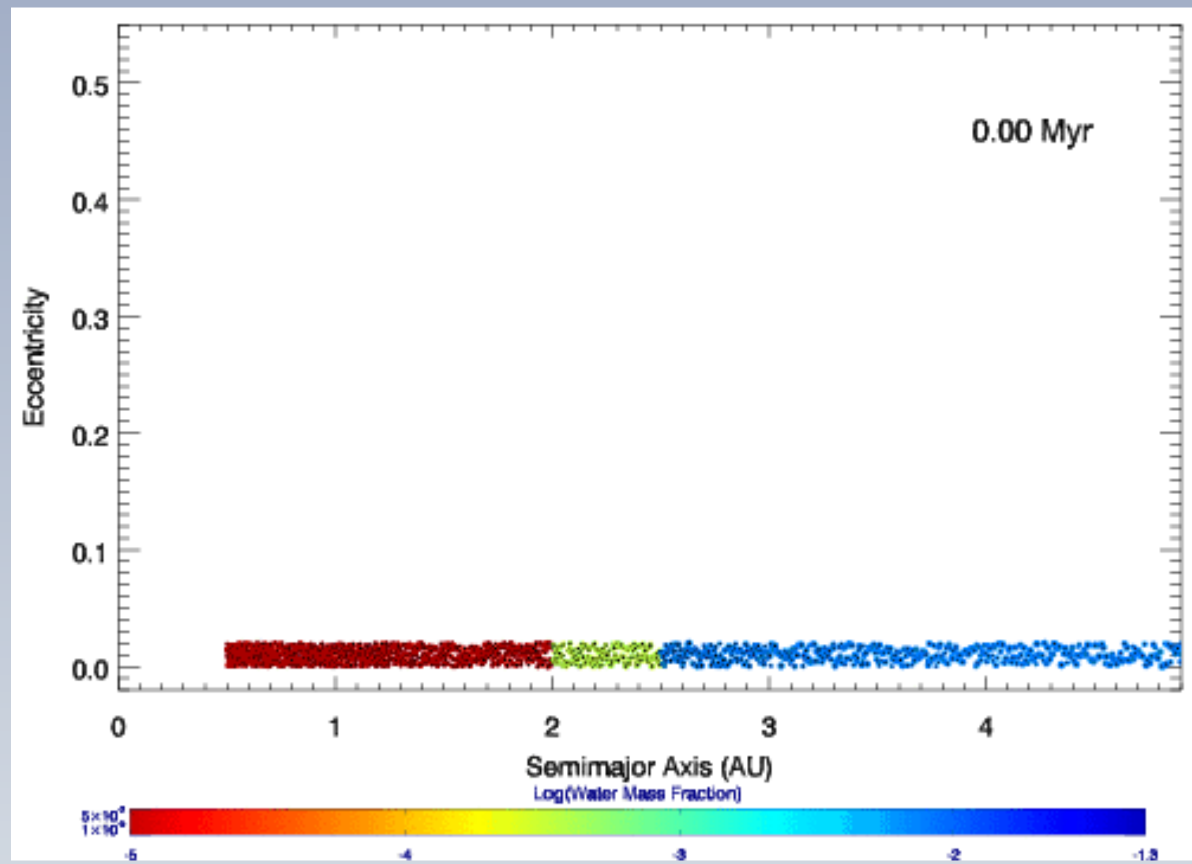
Dynamics of growth

Terrestrial planets

$v_{esc} < v_K$: terrestrial planets grow "in place"

High initial disk Σ:

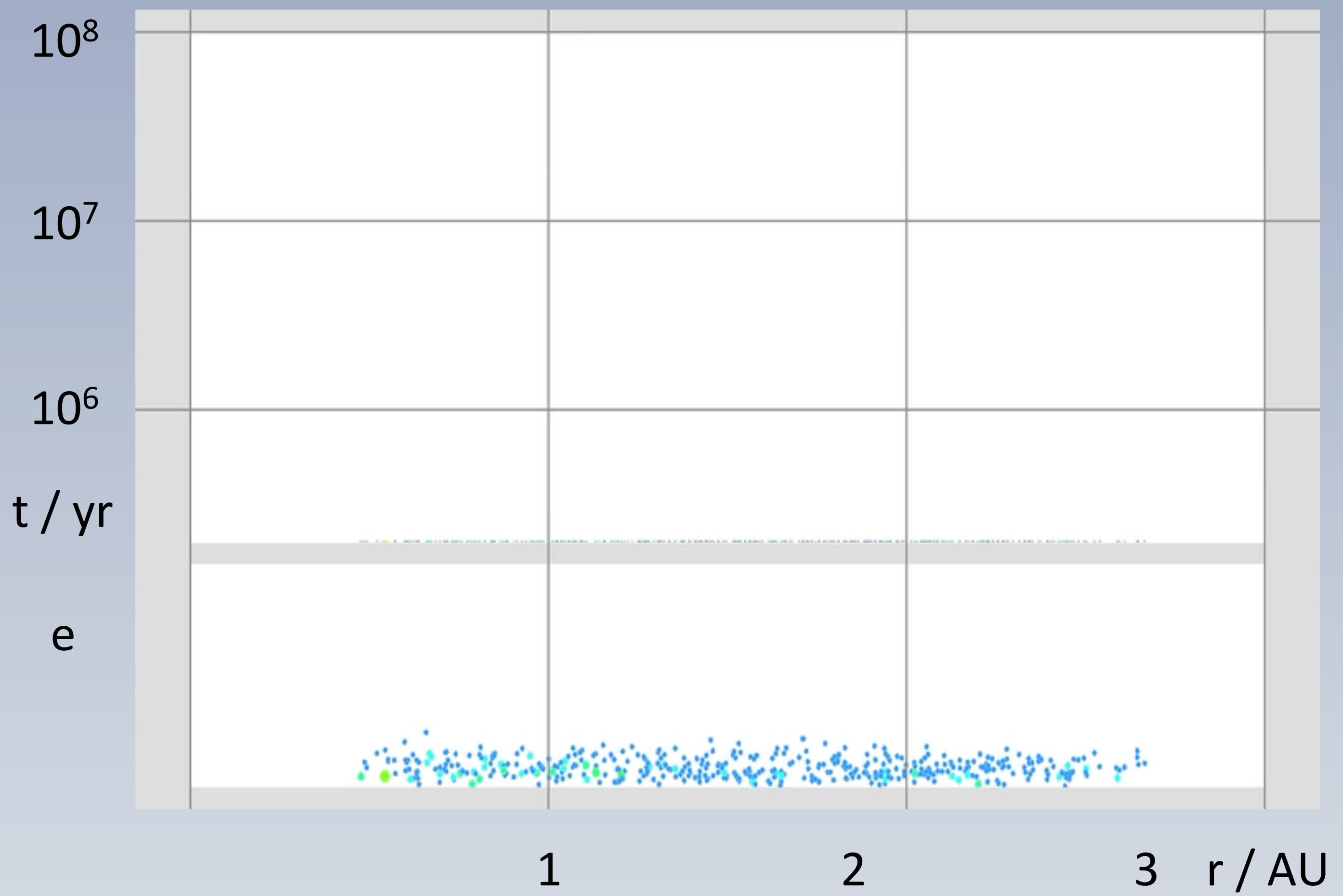
- more massive terrestrials
- fewer



simulation: Sean Raymond

Feeding zone narrow: collisions lead to low eccentricity

Dynamics of growth



Works well at leading order for the Solar System – largest discrepancy is over-prediction of mass of Mars…

Dynamics of growth

Giant planets

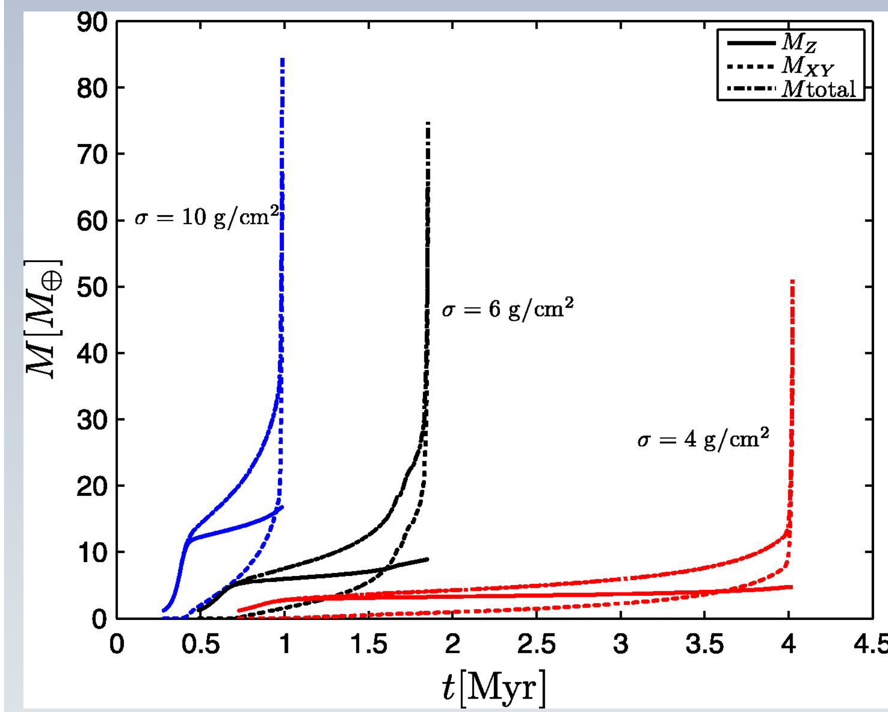
Require: form > 5 M_{Earth} *core* before gas is dissipated in ~ few Myr

too little mass in feeding zone

scatter rather than collide -> slow growth

~1-3 AU

~10-20 AU



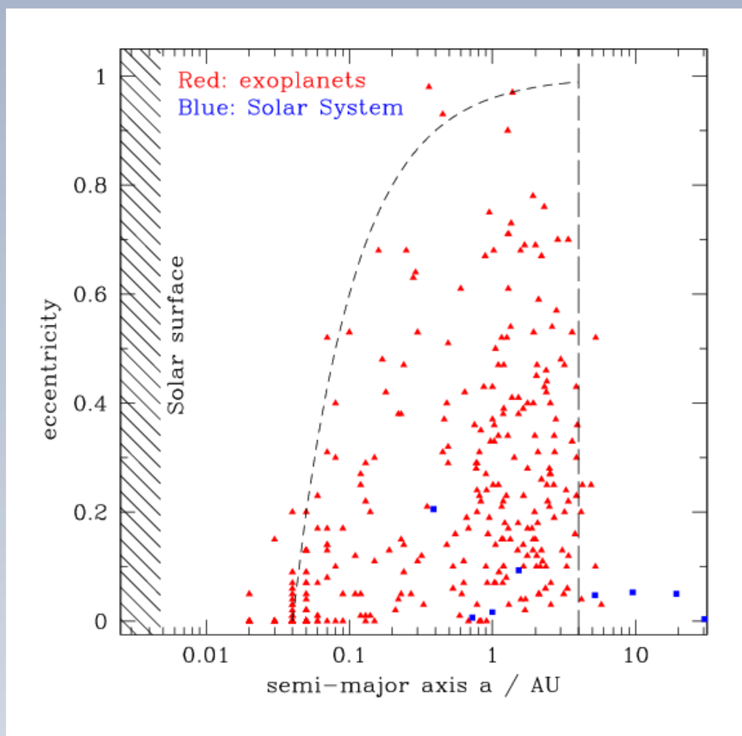
Large uncertainties due to envelope opacity (cooling) but consistent with Jupiter, Saturn to leading order

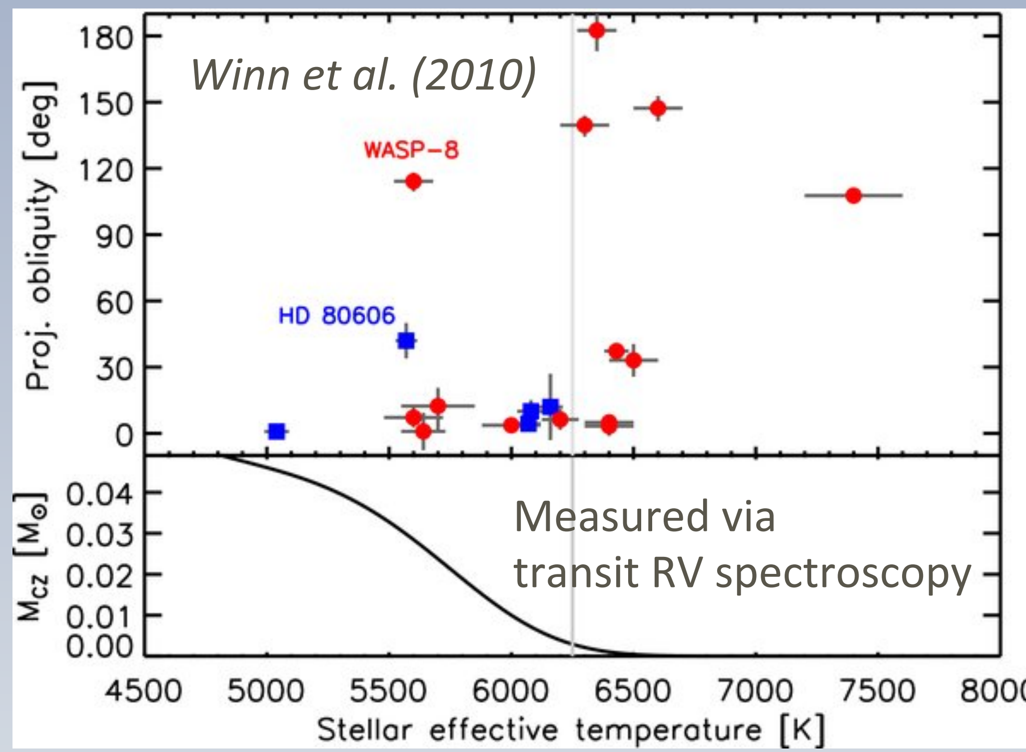
Movshovitz et al. 2010

Giant Exoplanets

Observations

Sky projected angle between stellar spin axis and planetary orbital axis





Require migration and eccentricity excitation

Hot Jupiters are sometimes misaligned or retrograde

Giant Exoplanets

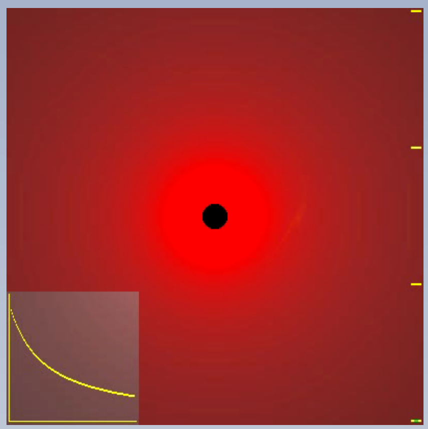
Observations

Working hypothesis: explained as consequence of

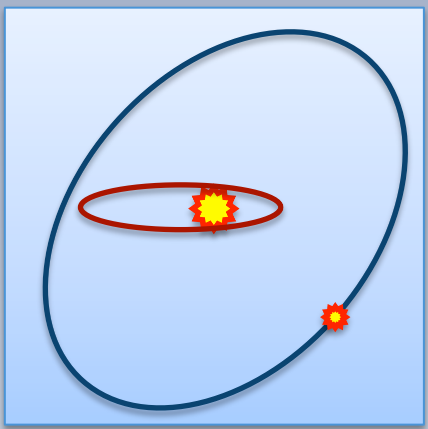
- “standard” giant planet formation (core accretion)
  - possibly at modestly smaller radii than in Solar System
- **evolution** due to exchange of energy and angular momentum with gas, other planets, binary companion

Giant Exoplanets

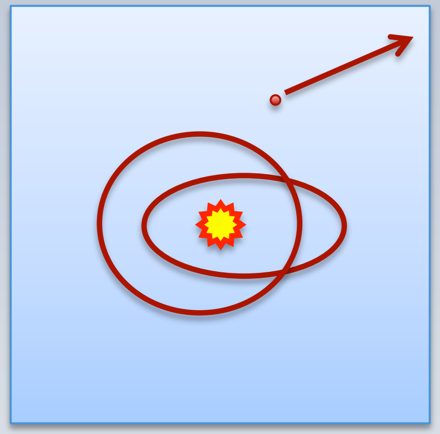
E, L exchange processes



Planet-gas disk interaction



Kozai-Lidov interaction (planet + misaligned binary)

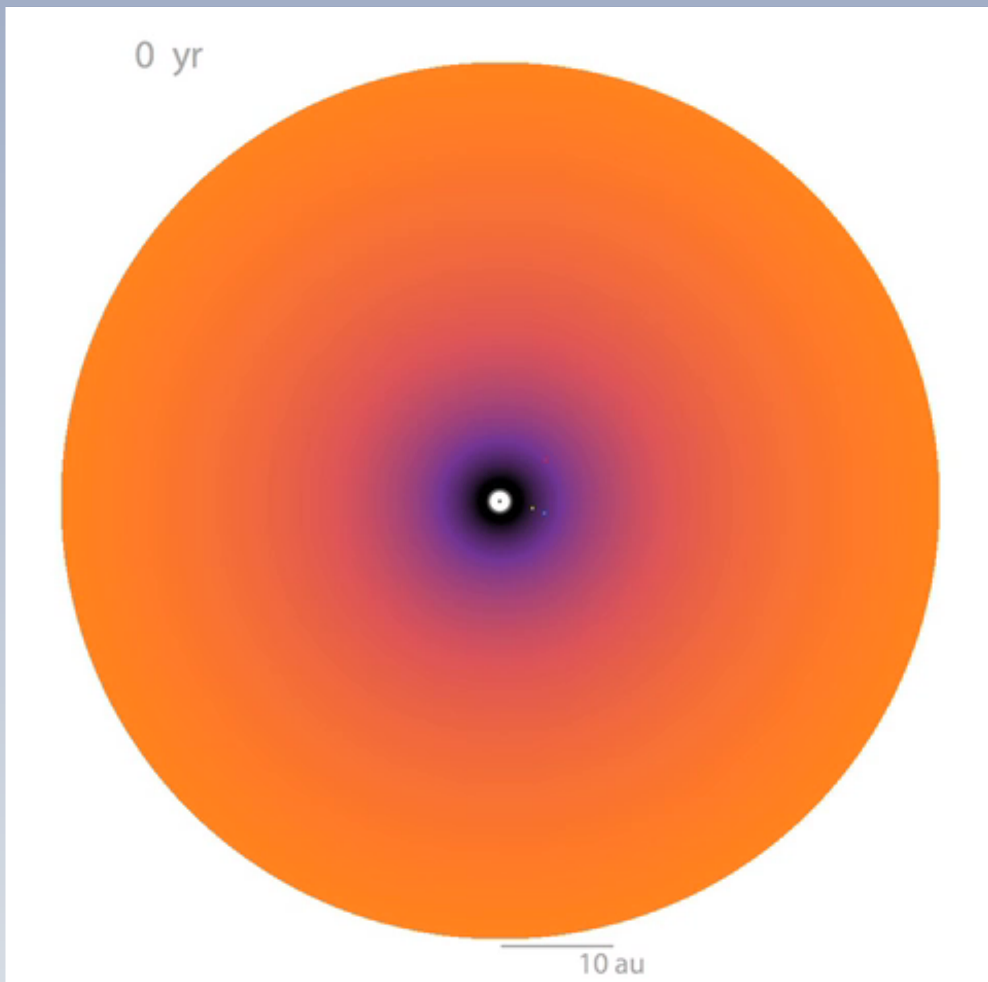


Planet-planet scattering

Secular chaos

Giant Exoplanets

Planet-planet scattering

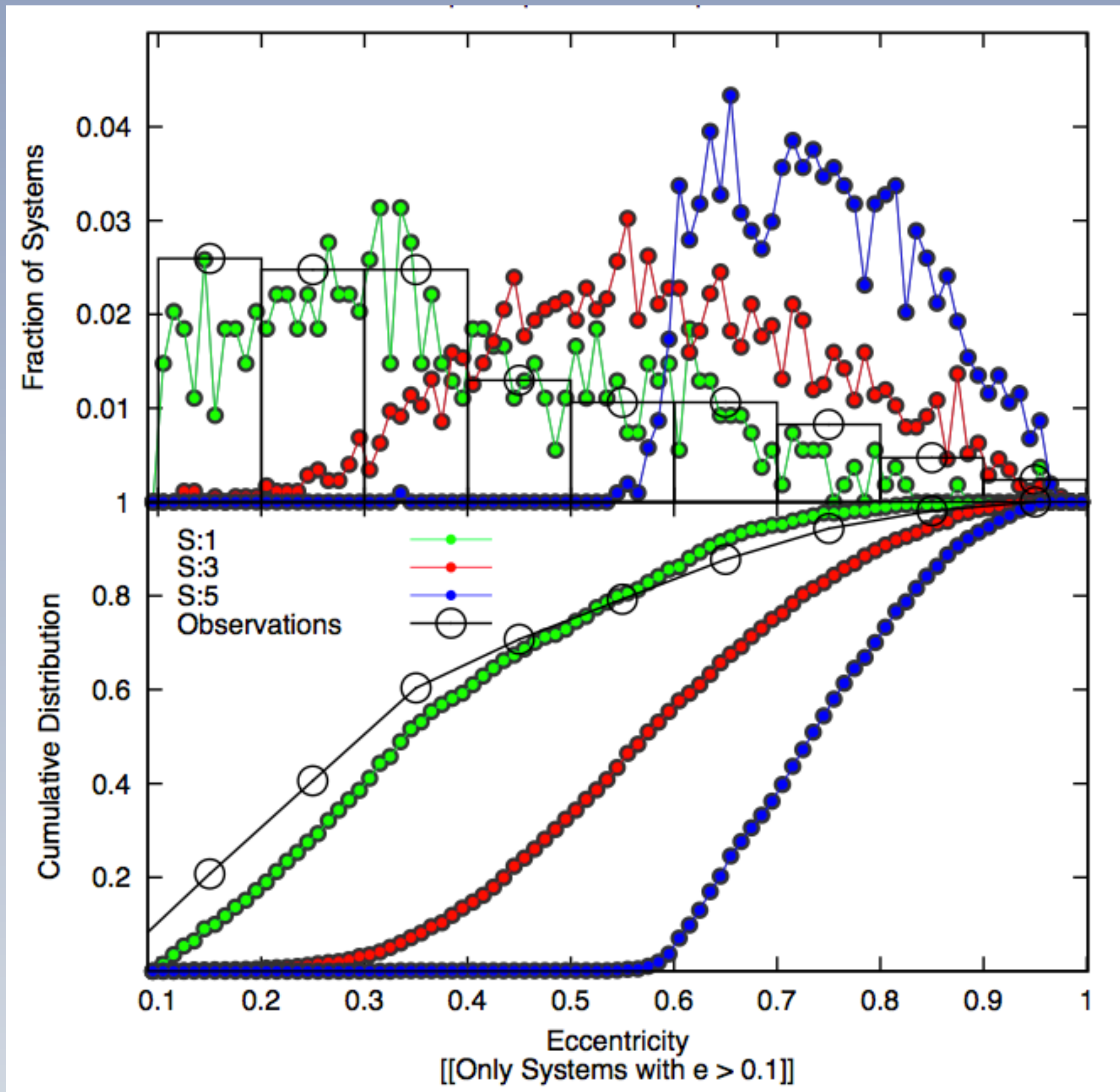


Moeckel & Armitage (2012)

Planet formation + migration typically leads to unstable multiple planet system as gas dissipates

Eccentricity and hot Jupiters form dynamically

Occurs early, but gas may be negligible to leading order

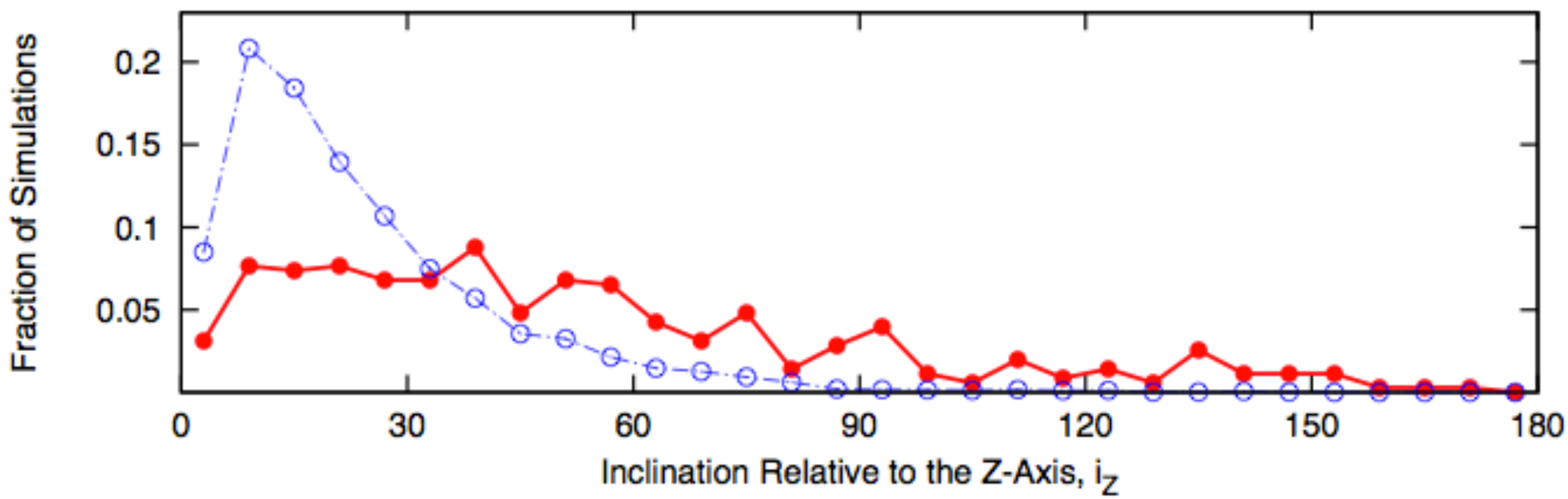


Initial conditions:
3 gas giants, circular orbits, forming as close as 1 AU

N-body only

Payne et al. (2014)

Match f(e) distribution for giant exoplanets 0.1 AU < a < 1 AU



Initial conditions:
3 gas giants, circular orbits, forming as close as 1 AU

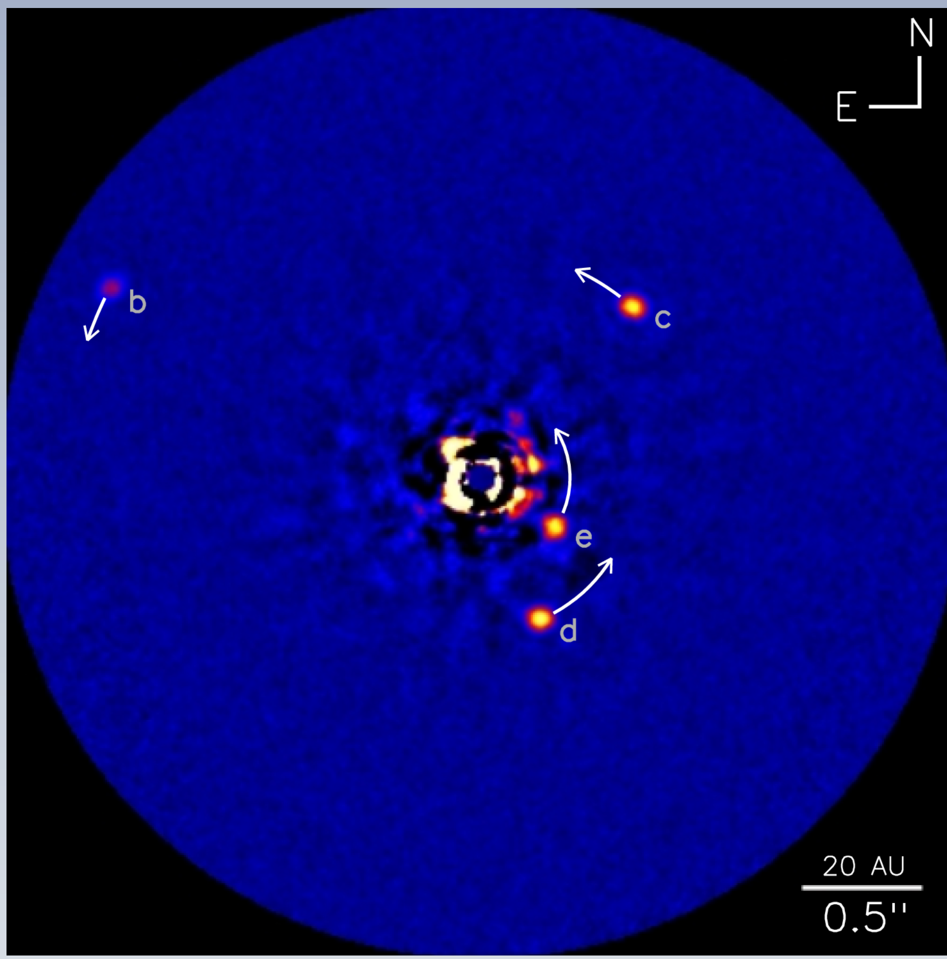
N-body only

Broad inclination distribution of planets scattered to e ~ 1 and then tidally circularized *(c.f. Nagasawa et al. 08; Beauge & Nesvorny 12)*

Scattering gives consistent but not unique solution to most close-in properties of giant exoplanets

Dynamics of growth

Large radii



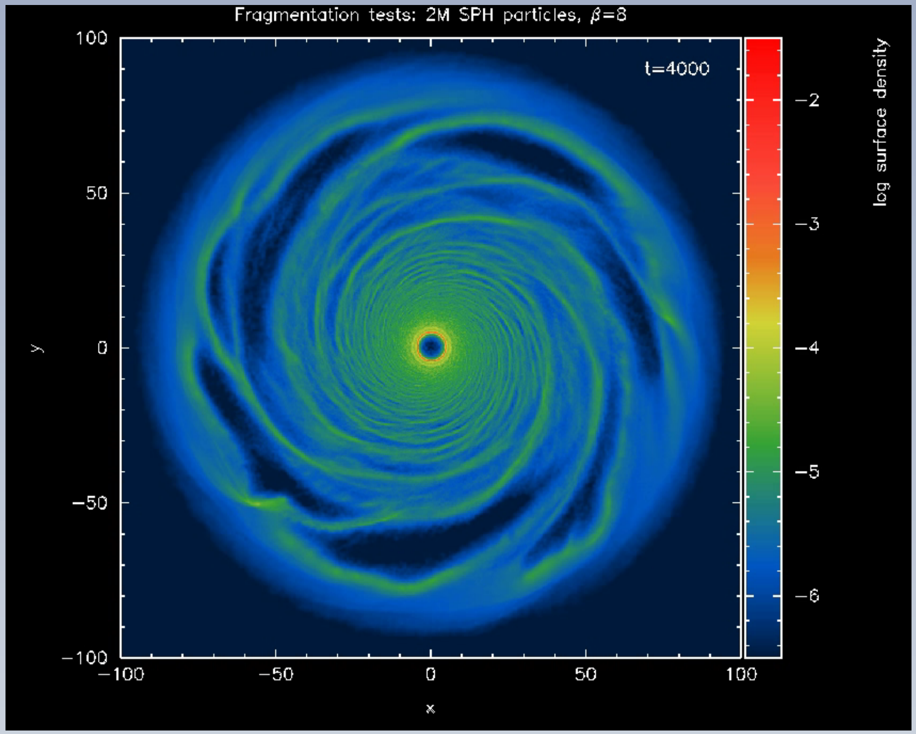
Marois et al. 2008

Neptune and extrasolar planets at “large” radii (50 AU) are also incompatible with *in situ* core accretion

HR8799 and other directly imaged systems critical constraints

Dynamics of growth

Large radii



First evidence for a new gravitational instability channel for giant planet formation?

Predicted to be inevitable for large massive disks, but hard to keep masses below brown dwarf scale…

(Rice et al. 2010; Kratter et al. 2010)

OR – multiple cores formed at smaller scales, migrated out, and later accreted gas?

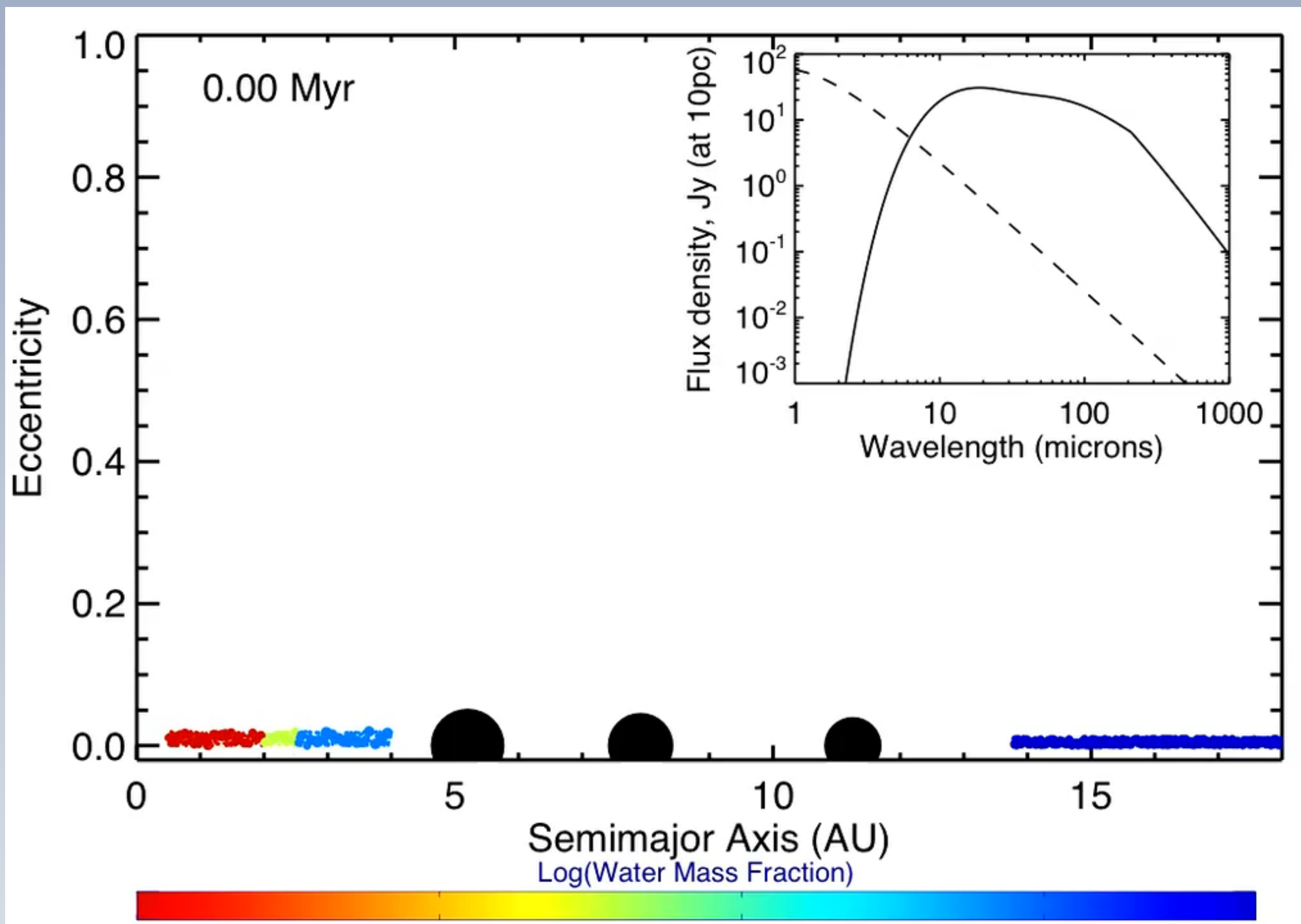
Need more data….

Terrestrial Exoplanets

Theory

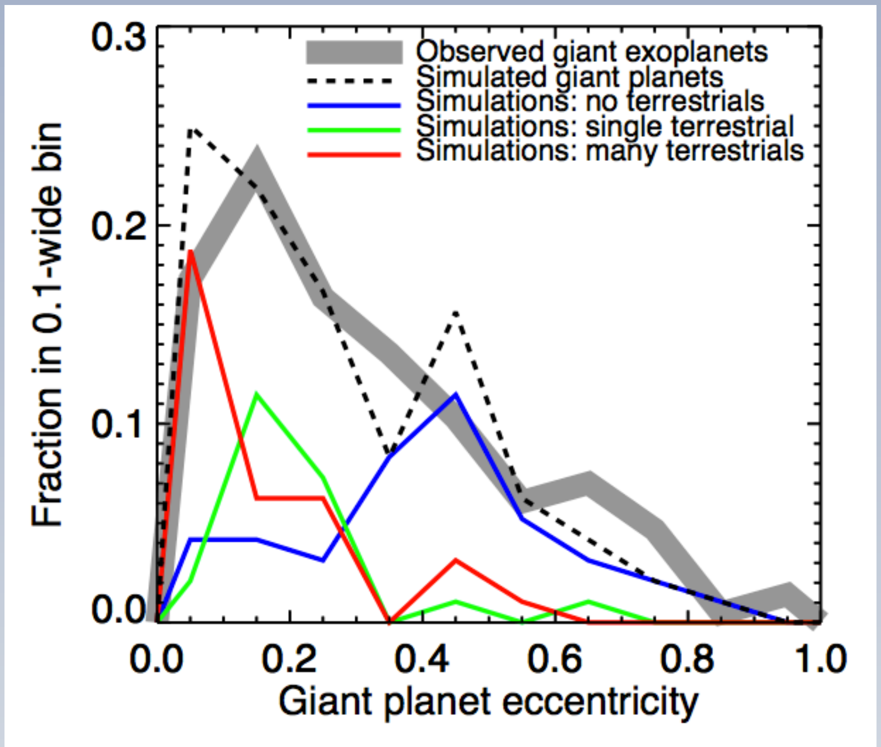
- “Solar System-like”
  - slow (~100 Myr), hence gas free
  - in place
  - ~independent of giant planets
- Giant-controlled
  - substantially impacted by violent giant planet dynamics
- Migration dominated
  - orbital evolution among *terrestrial precursors*

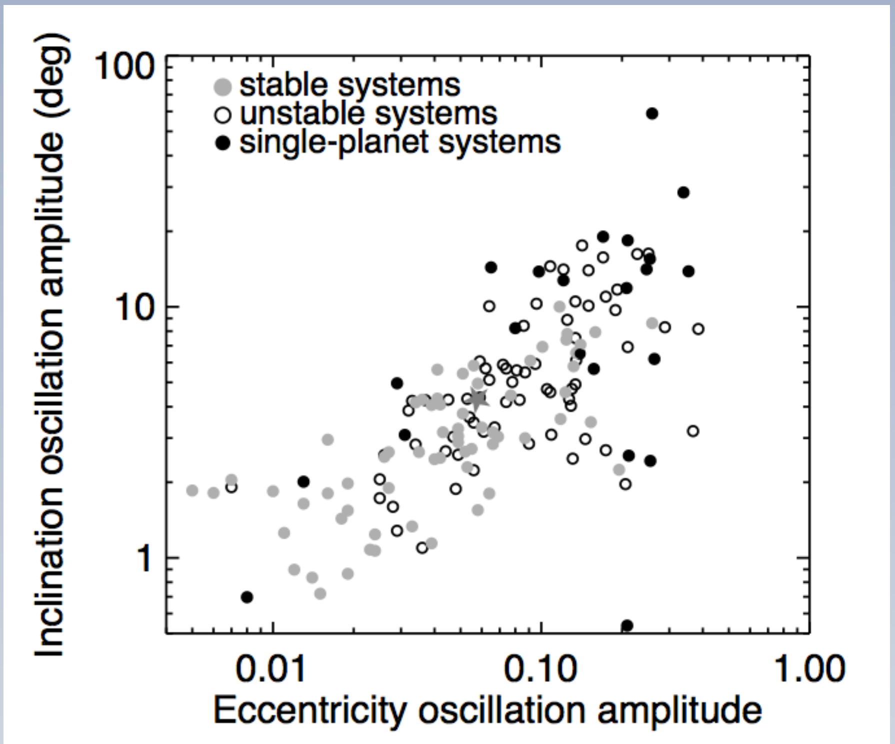
Giant dominated



Assume planet-planet scattering dominant (*Raymond et al. 2011, 12)*

Terrestrial Exoplanets
Theory

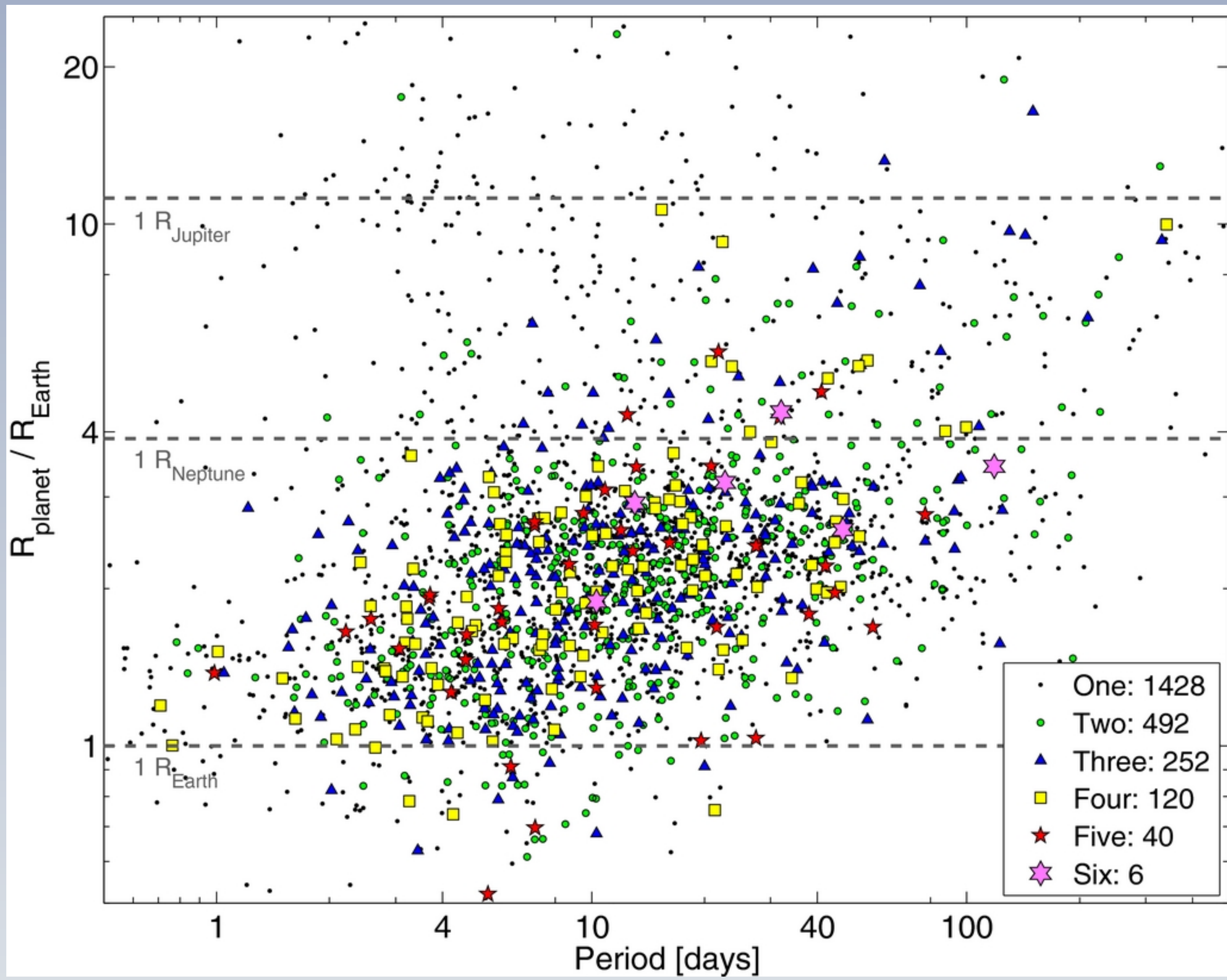




Rich terrestrial planet systems live in systems with near-circular giant planets

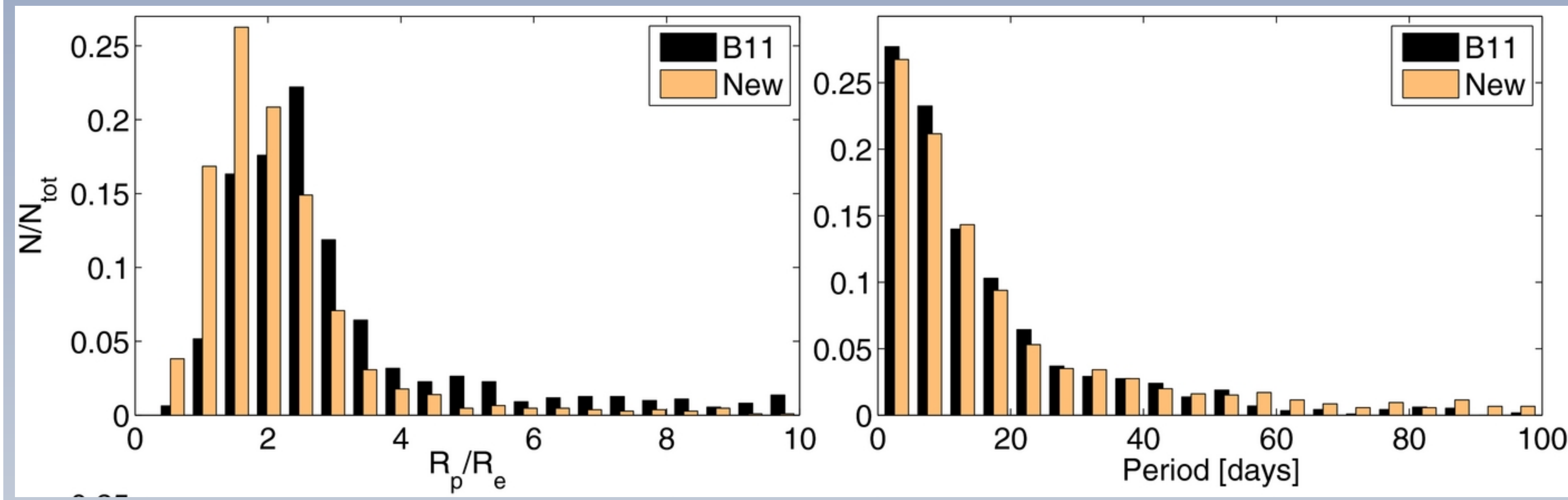
Predict currently unobserved population of dynamically excited terrestrials

Kepler systems



Batalha et al. 2013

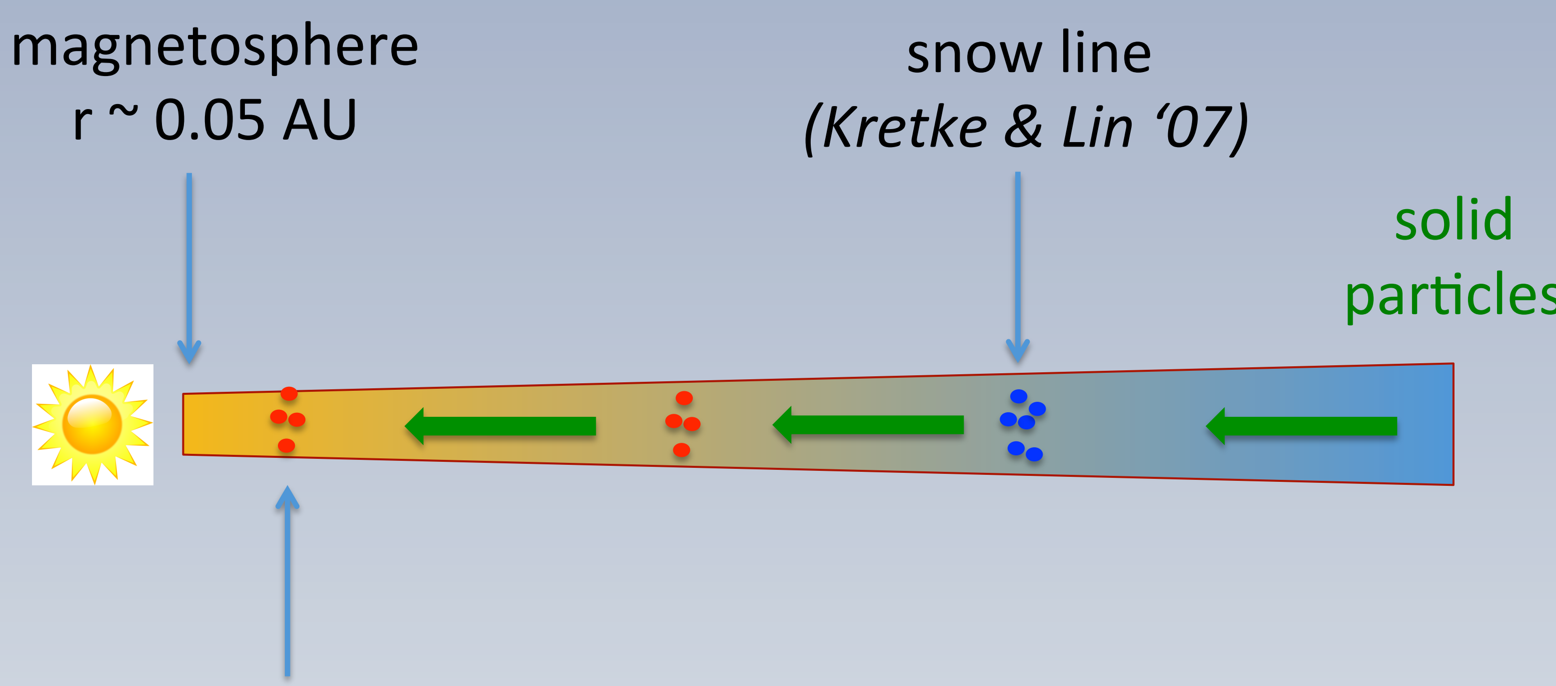
2 obvious challenges for theory…



High abundance of planets with radii not represented in Solar System… what are these planets?

Many stars with close-in planetary systems, where formation time is so short ($<10^5$ yr) that gas disk effects **must** be important

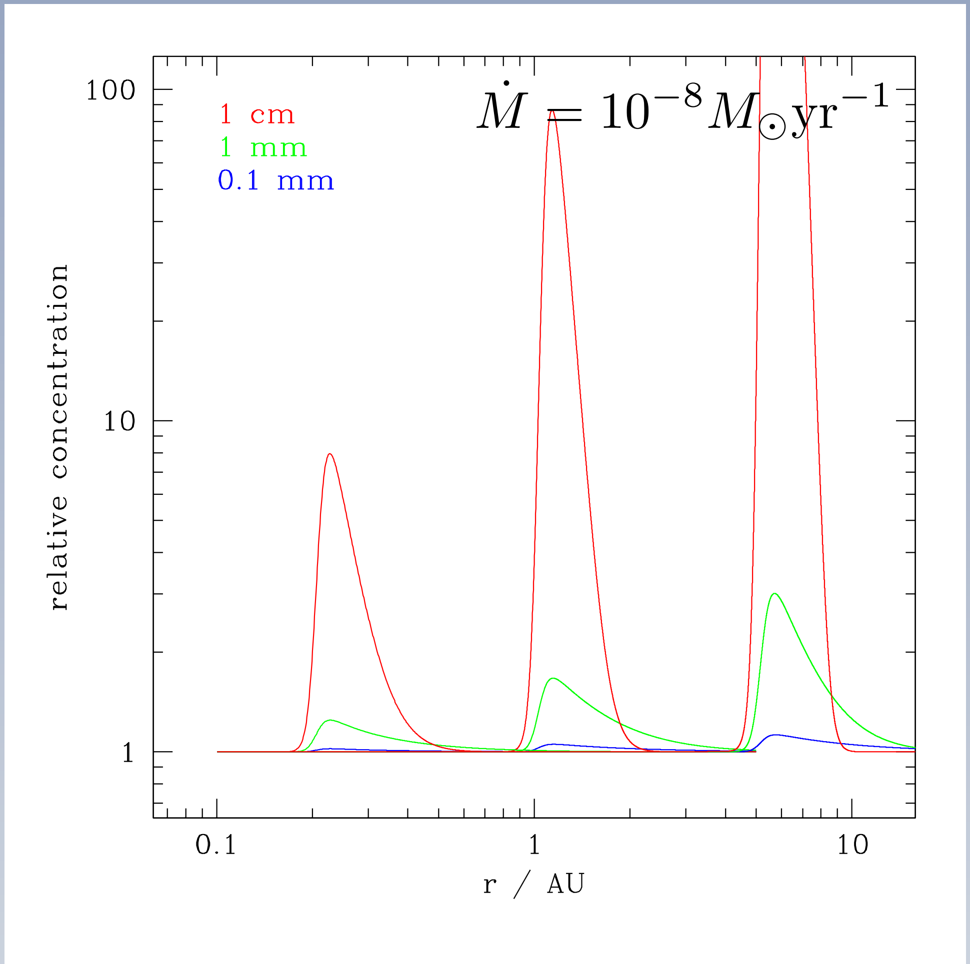
evidence for a migration dominated mode?



inner edge
of dead zone
T ~ 800 K

solids drift radially inward under aerodynamic drag and encounter **traps** in disk *(Hasegawa & Pudritz 11)*

planetesimal formation at traps



$\alpha_{in} = 10^{-2}$, $\alpha_{out} = 10^{-3}$, width w = 2h

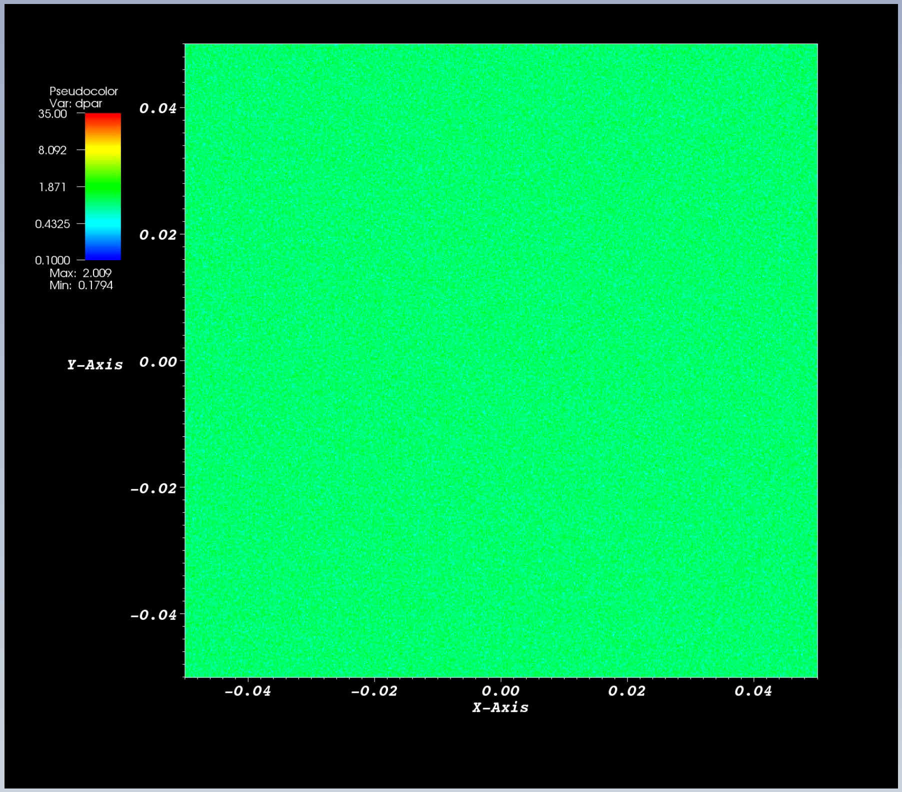
c.f. coagulation models of Drazkowska et al. (2013)

Local pressure maxima trap particles of sizes formed from coagulation (mm-cm) readily, especially in outer disk

If gas disk has local maxima, particle density much higher at these locations

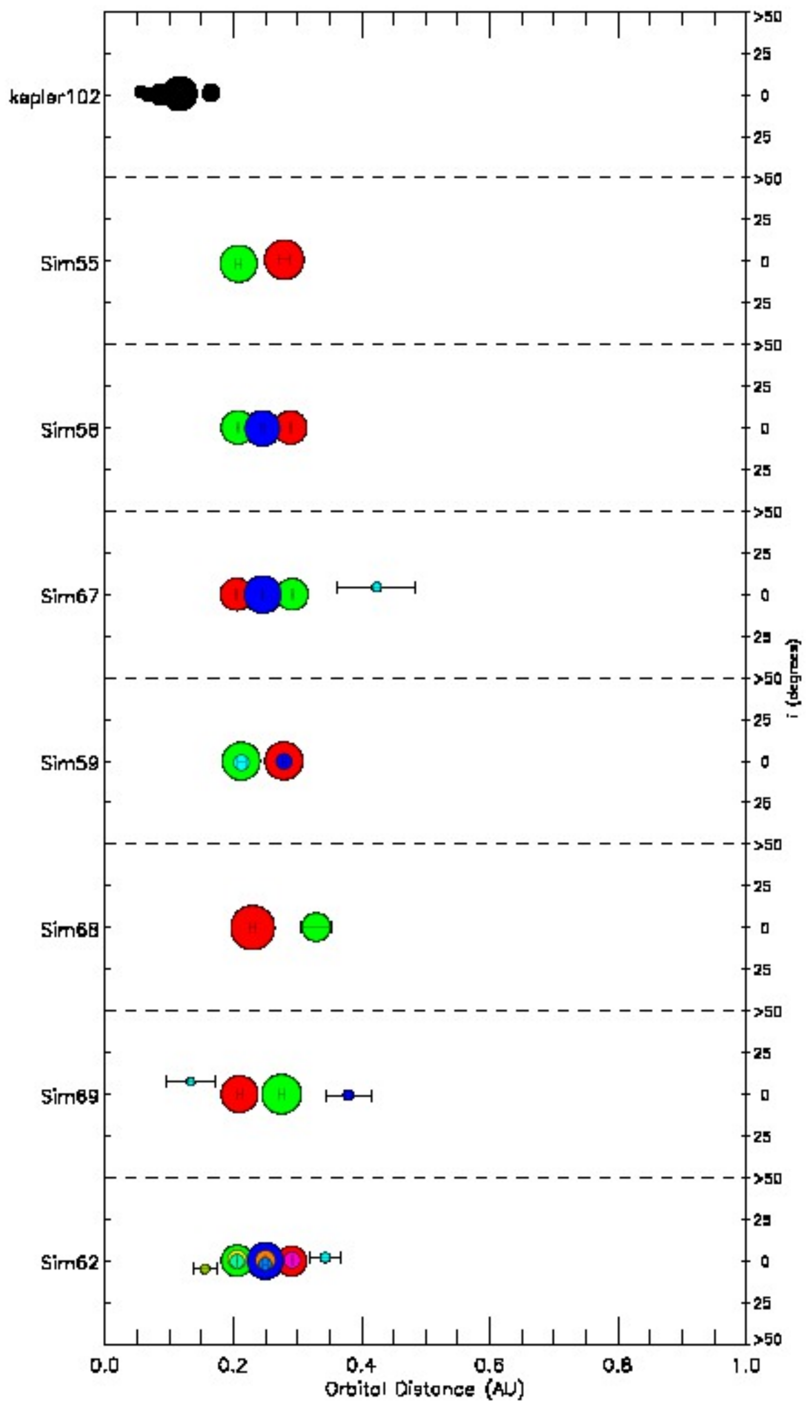
high densities lead to planetesimal formation via collective instabilities

"Least problematic" route to planetesimal formation from small particles involves instabilities in coupled gas / particle mixtures *("streaming instability", Youdin & Goodman 2005)*



2D streaming: Jake Simon

Require locations in disk where $\rho_{particle} / \rho_{gas}$ > threshold to form planetesimals… in a disk with traps this will be at the location of the traps



formation of planets if planetesimals form at preferred location in inner disk

produce packed multiple systems for mass fluxes of ~10 M_{Earth} / Myr into traps in inner disk

also form co-orbital planets…

not yet clear if orbital properties are better or worse match to *Kepler* systems than in situ models

Bruns & Armitage, in prep

Summary

Solar System appears to be a planetary system where the giant planets were only *moderately dynamically active*, and the mass in the terrestrial region was low enough that the Earth & Venus formed after the gas was gone

More active giant planets (higher mass, closer together, less damping from Kuiper belt) are common – result in eccentric extrasolar gas giants, hot Jupiters

More mass in (or migrating through?) the terrestrial region forms low mass planets earlier – close-in Kepler systems?