Inside-Out Planet Formation

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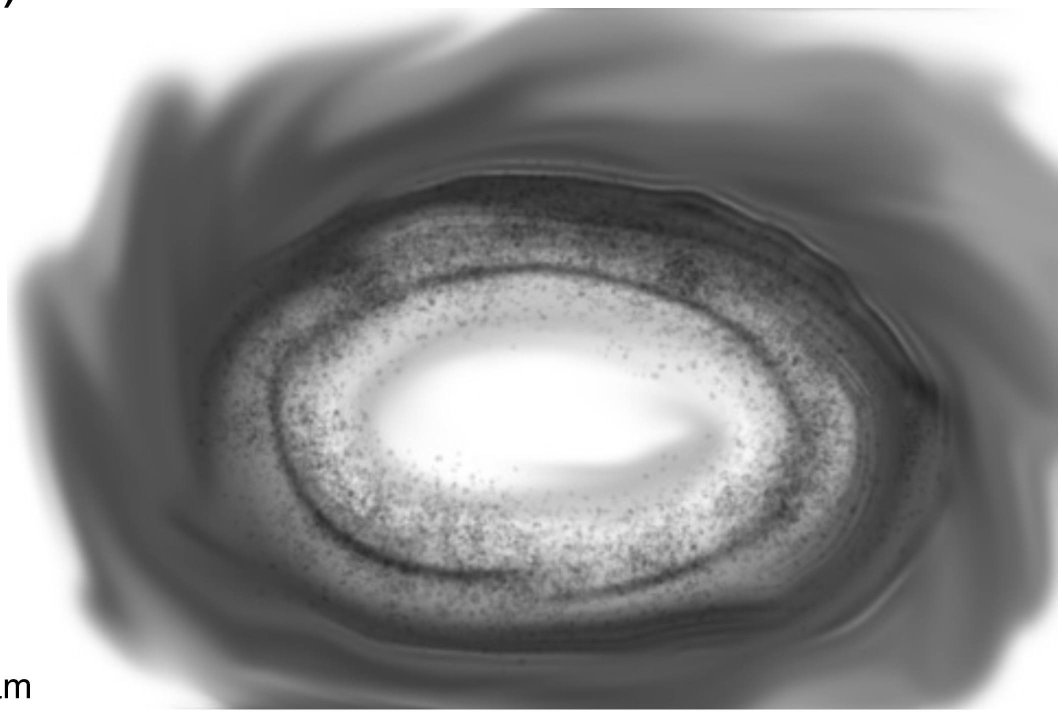

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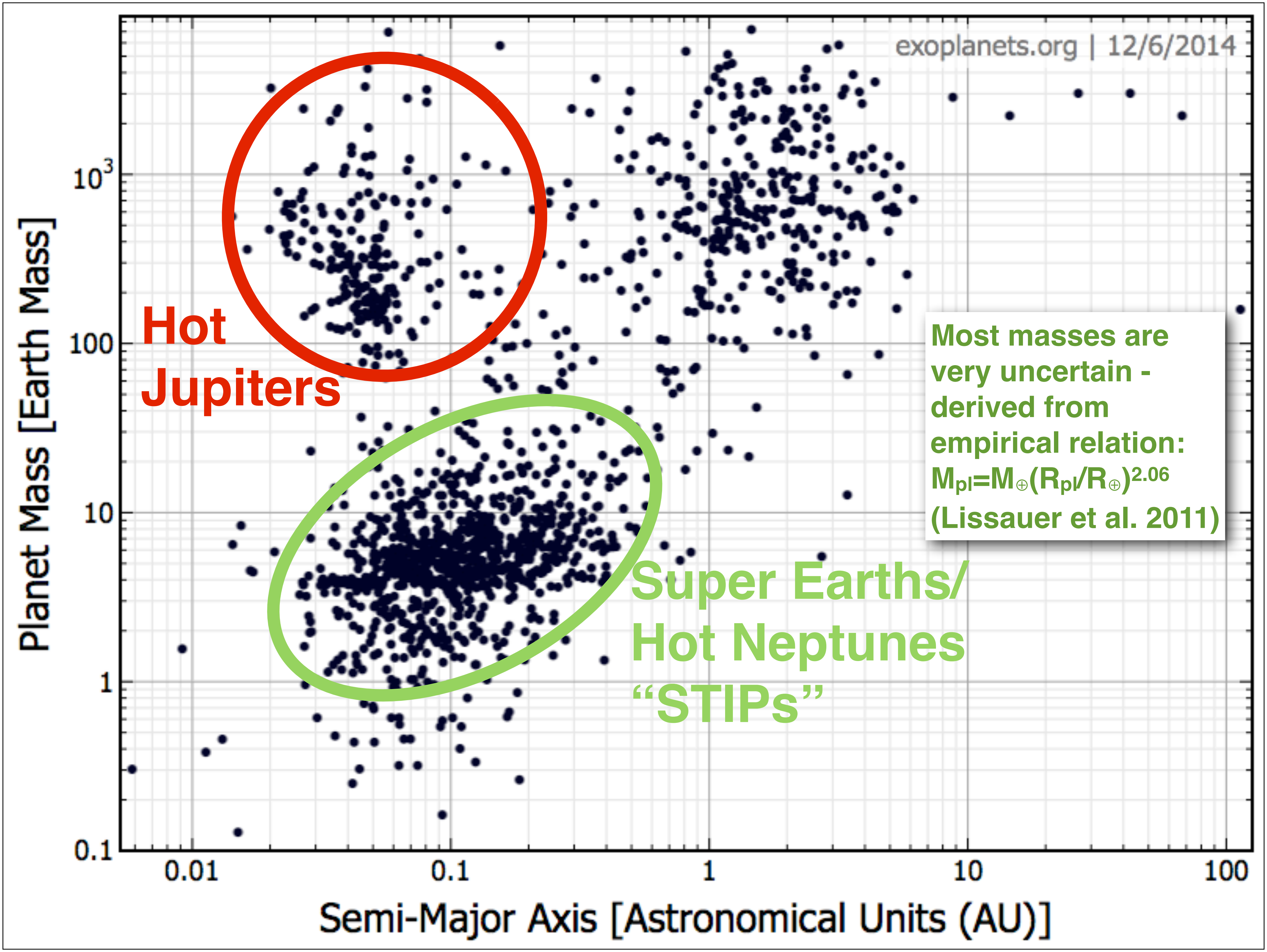
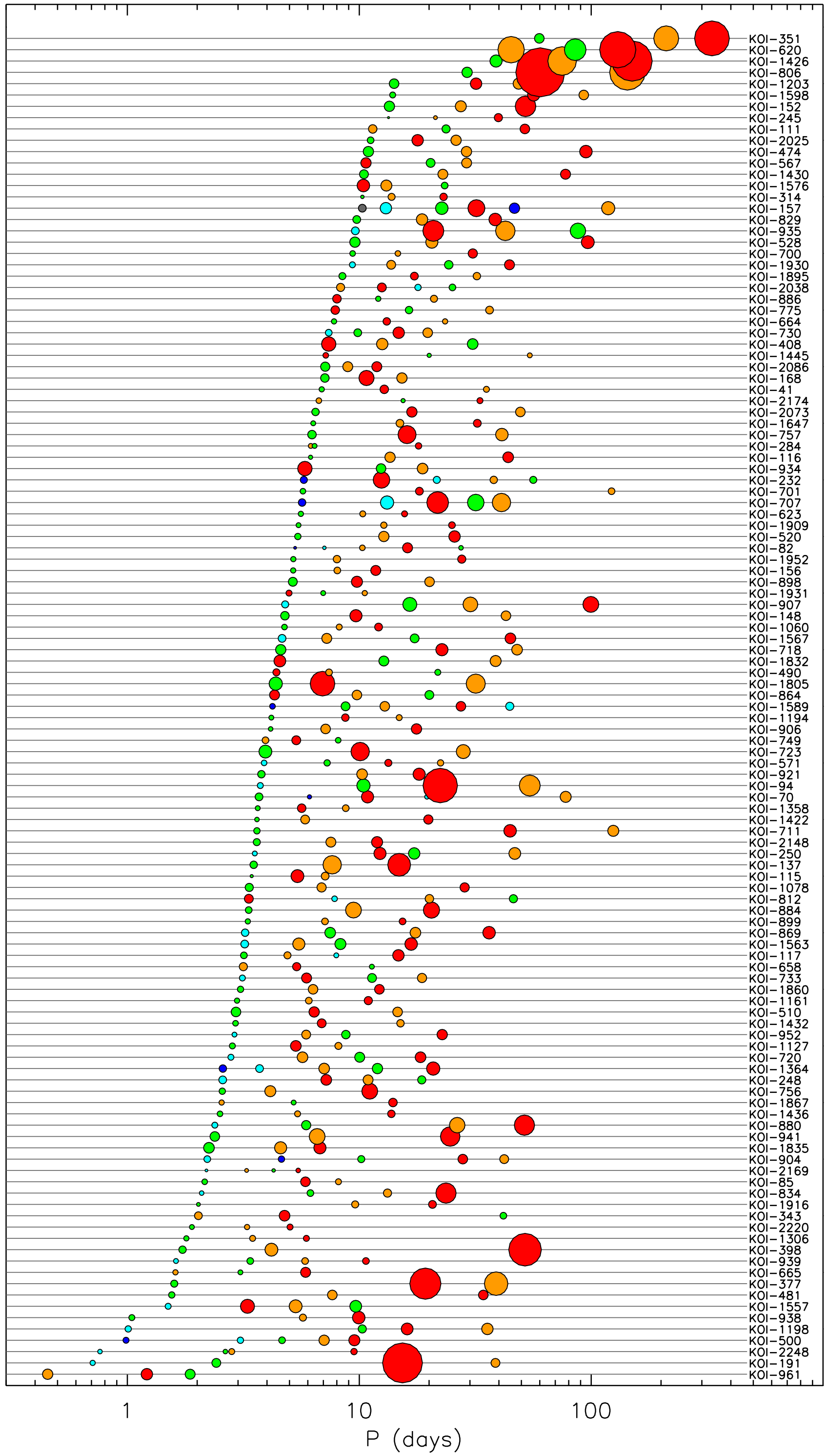

exoplanets.org | 12/6/2014
Planet Mass [Earth Mass]
10^3
100
10
1
0.1
0.01
0.1
1
10
100
Semi-Major Axis [Astronomical Units (AU)]
Hot Jupiters
Super Earths/ Hot Neptunes "STIPs"
Most masses are very uncertain - derived from empirical relation:
$M_{pl}=M_{\oplus}(R_{pl}/R_{\oplus})^{2.06}$
(Lissauer et al. 2011)

Systems with Tightly-packed Inner Planets (STIPs)



Fabricky et al. (2014)

Properties of STIPs

Ragozinne (2013 - From Stars to Life)

- ≥3 planets per system
- Sizes of ~1-3 $R_{\oplus}$, consecutive planets have similar sizes or slightly bigger
- Periods from ~1-100 days; peak at ~10-20 days
- Tightly-packed (period ratios near 1.5-3; separations of ~10-20 R_{Hill}), but not on verge of instability
- Mostly non-resonant period ratios, but ~10% just wide of 1st order resonances (mostly 2:1 & 3:2)
- Low dispersion in inclinations (≲3°)
- Wide range of densities
- Occur around tens of percent of (single) stars
- May be the dominant mode of planet formation

Migration or In Situ Formation?

Migration

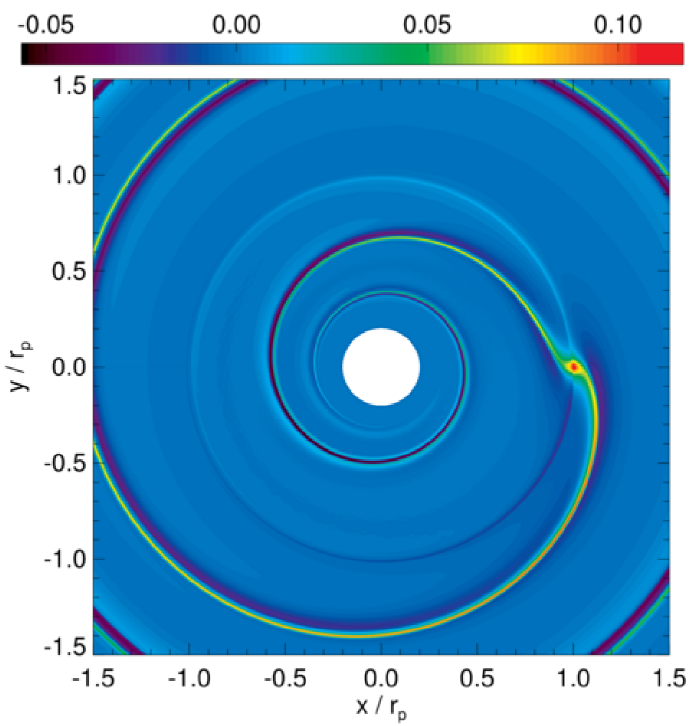
(e.g., Alibert et al. 2006; McNeil & Nelson 2010; Kley & Nelson 2012)

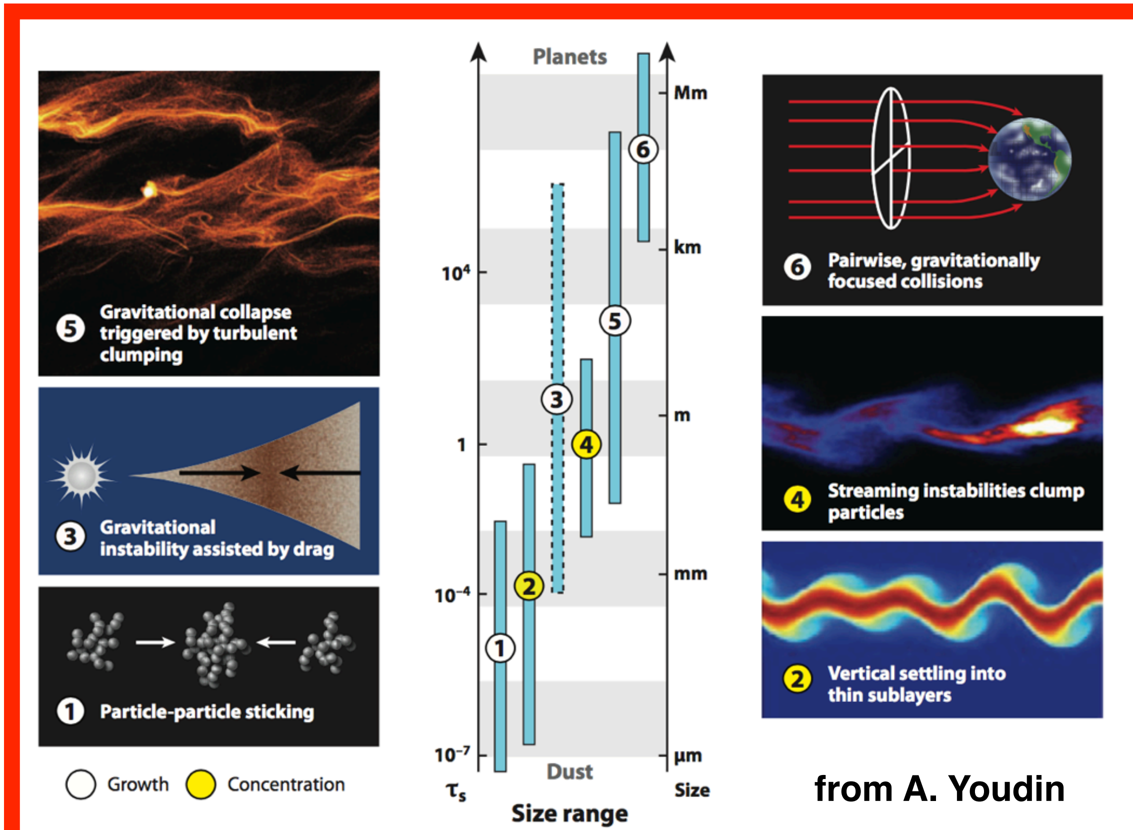
- Form planets in outer disk

?

Core Accretion
(c.f. Gravitational Instability)
But still many open questions, including the *meter-sized barrier*

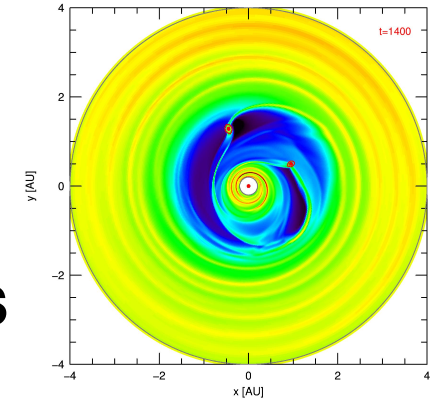
- Migration to inner disk

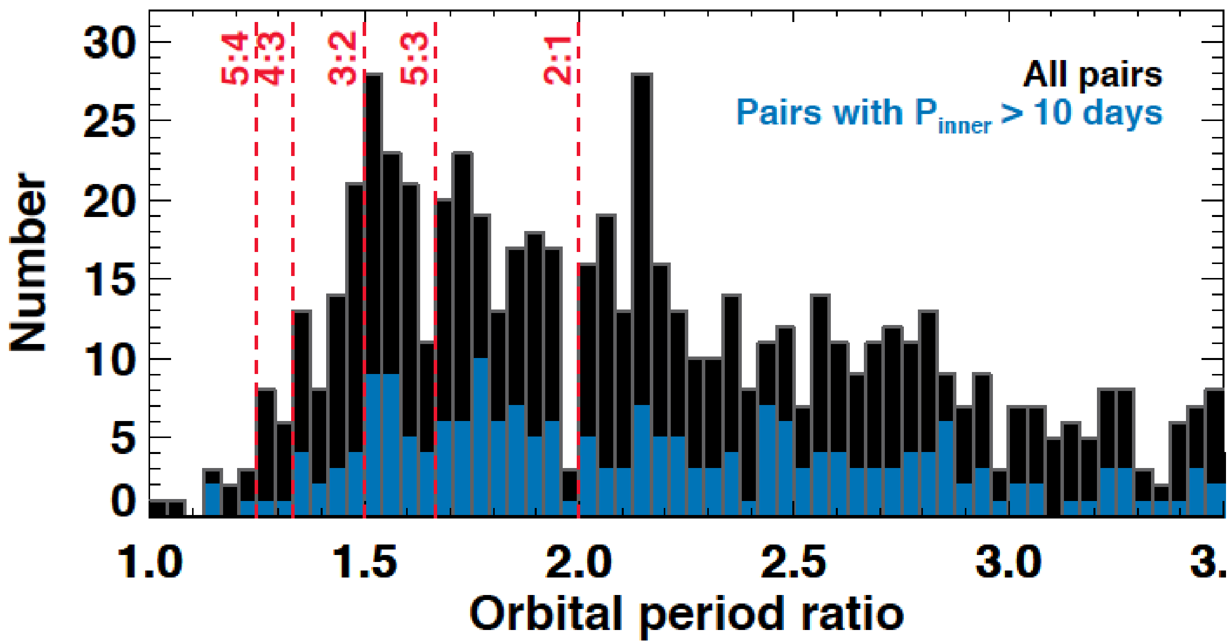




Migration or In Situ Formation?

Migration (e.g., McNeil & Nelson 2010; Kley & Nelson 2012)
- Form planets in outer disk
- Type I or Type II migration to inner disk
- **Expect pile-ups of orbits near resonances**





But most STIPs pairs are non-resonant
(Fabrycky et al. 2014; Baruteau et al. 2014)

So mechanisms invoked to prevent trapping in resonances
(Stochastic Turbulent Migration: Rein 2012; Eccentricity damping during migration: Goldreich & Schlichting 2014)

and/or move planets out of resonance (e.g., Papaloizou 2011; Lithwick & Wu 2012; Batygin & Morbidelli 2013).

Migration or In Situ Formation?

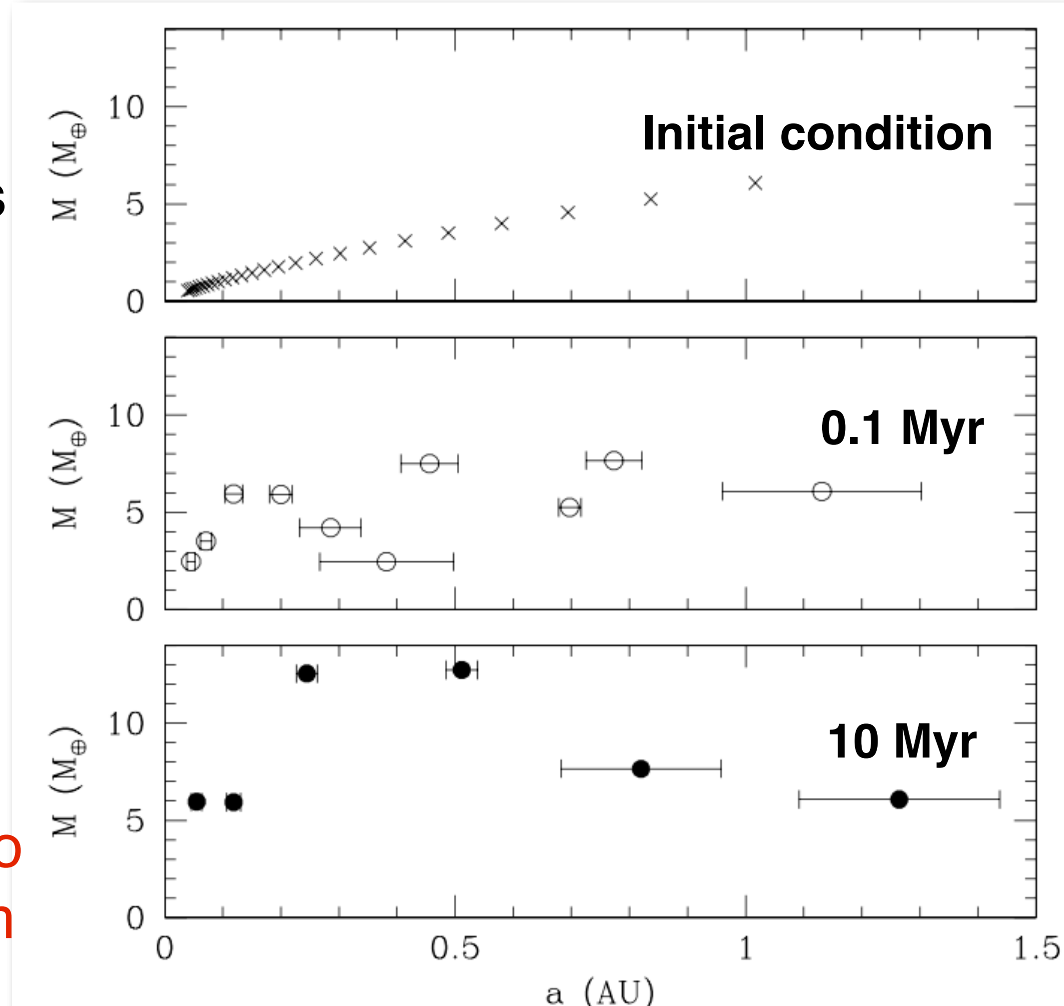
In Situ Formation: Hansen & Murray (2012, 2013)

- Concentration of solids (~20-100 M_E inside ~1AU) arranged in an inner enriched disk of protoplanets

- They model final stages of **oligarchic growth** of planets (Ida & Lin 1998; Kokubo & Ida 2002)

- Some of the initial protoplanets are already >1$M_\oplus$

- Orbital evolution with gas leads to orbital architectures that differ from observed systems (Ogihara, Morbidelli & Guillot 2015)



(see also Chiang & Laughlin 2013)

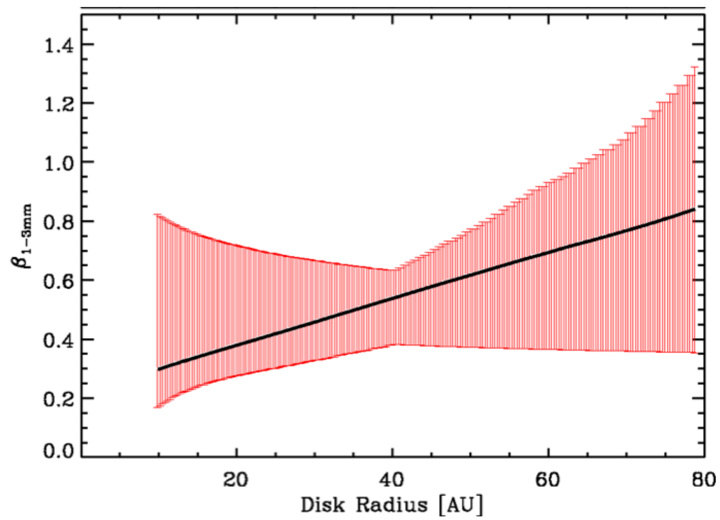
Observational Evidence

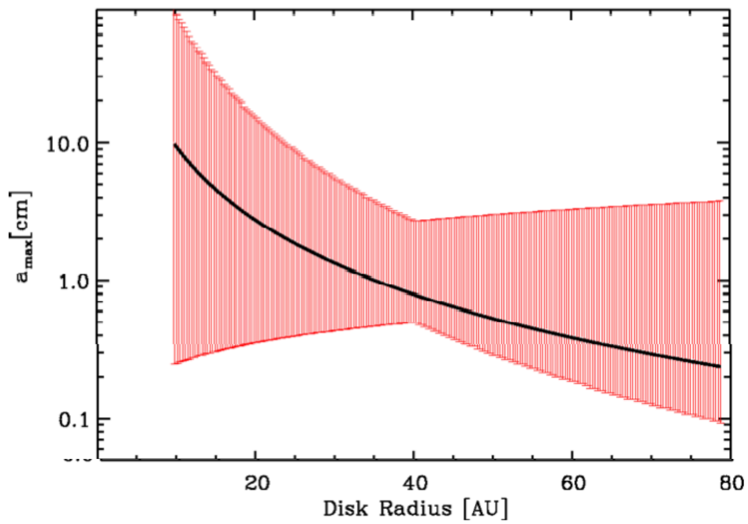
Grain Growth in Disks

CQ Tau

Trotta et al. (2013)

see also, e.g., Perez et al. (2012); Testi et al. (2014).





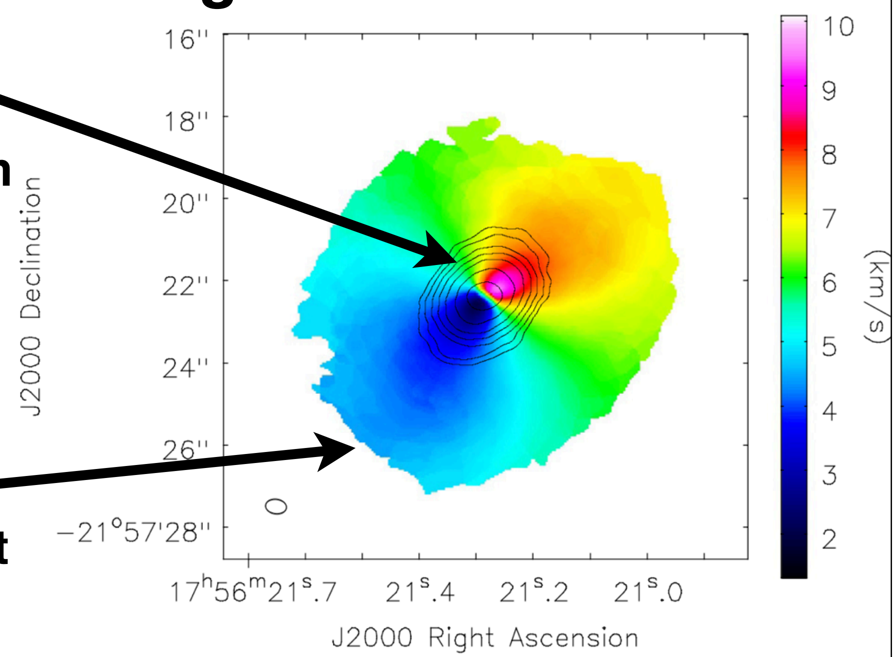
Inward radial drift of dust with respect to gas

HD 163296

de Gregorio-Monsalvo et al. (2013)

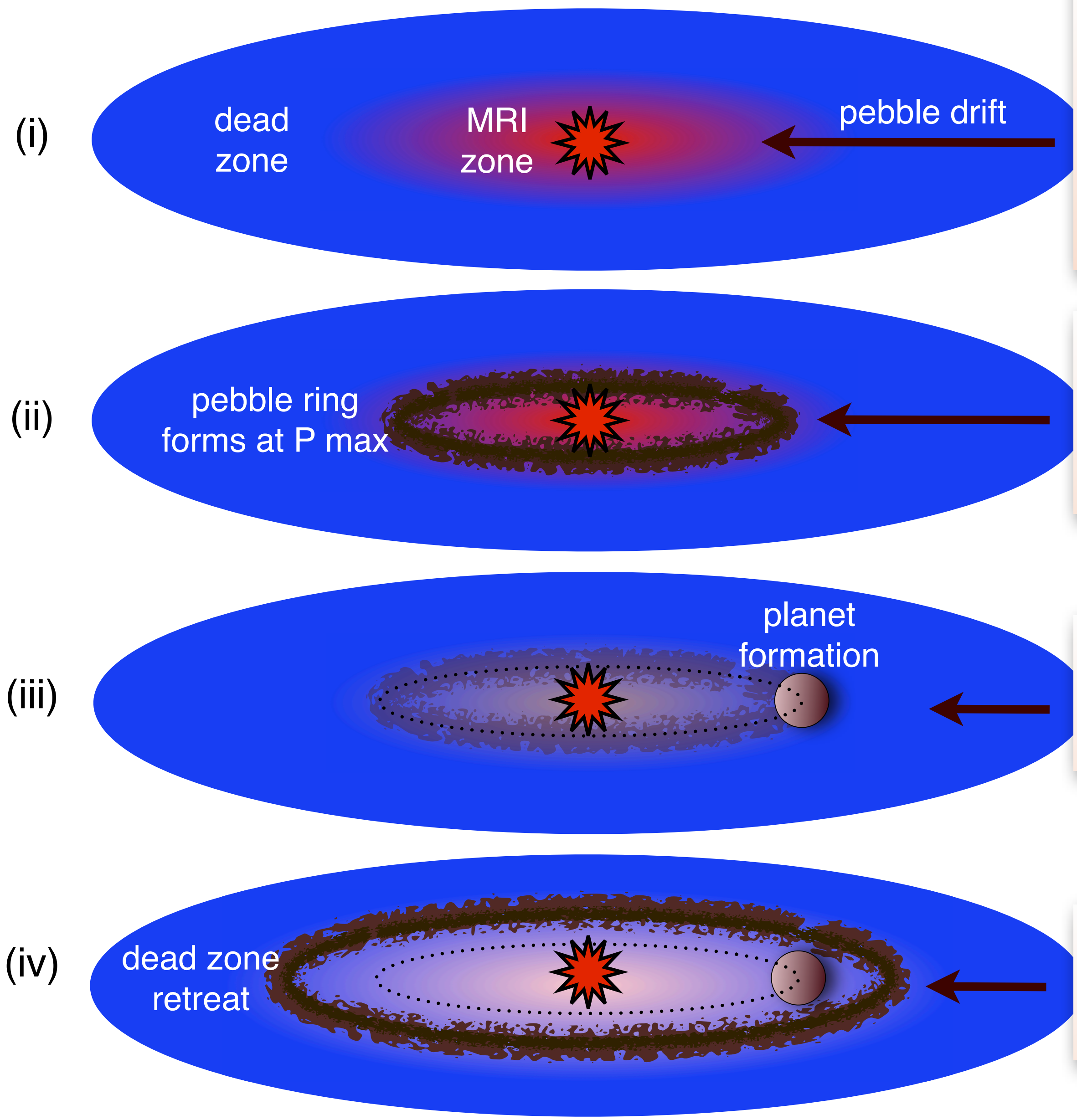
850μm dust continuum

CO(3-2) 1st moment



Overview of Inside-Out Planet Formation

Chatterjee & Tan (2014)



Rapid radial drift of cm to m-sized “pebbles” via gas drag. They collect at the pressure maximum at the **dead zone inner boundary (DZIB)**, likely first set by thermal ionization of alkali metals at ~1200K.

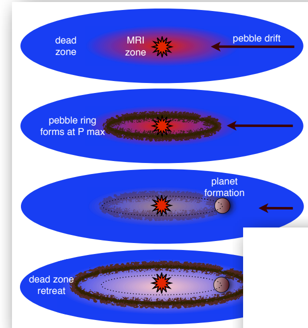
Pebbles concentrate in narrow ring. Begin to dominate local gas mass surface density, $\Sigma_p > \Sigma_g$, eventually by factors ~10.

A planet forms from the pebble ring. It grows to then clear a gap, leading to viscous clearing of the inner disk.

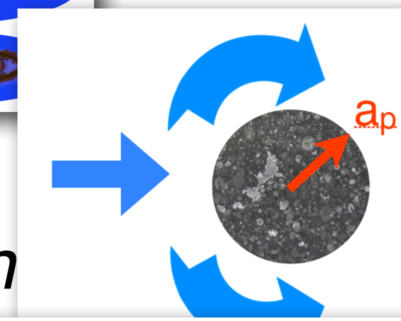
With reduced extinction from the inner disk, the DZIB retreats outwards and the process repeats.

Overview of Inside-Out Planet Formation

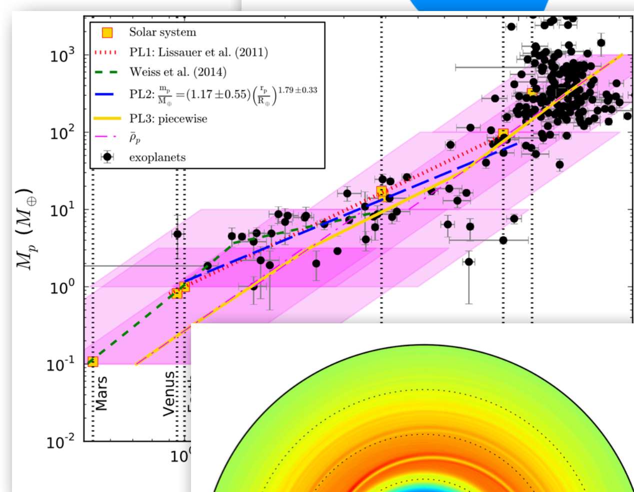
• Chatterjee & Tan, 2014, ApJ, 780, 53,
Inside-out Planet Formation



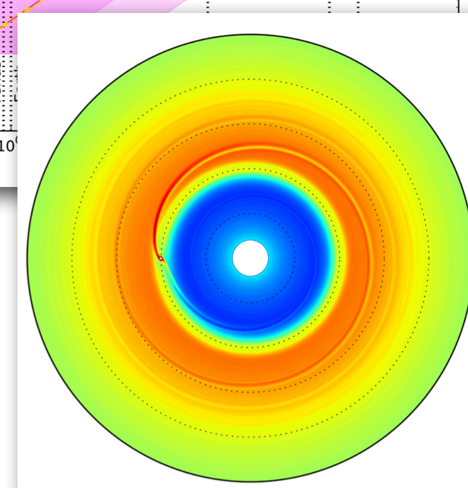
• Hu, Tan & Chatterjee 2014, IAUS, 310, 66,
Pebble Delivery for Inside-Out Planet Formation



• Chatterjee & Tan, 2015, ApJ, 798, L32,
Vulcan Planets: Inside-out Formation of the Innermost Super-Earths



• Hu, Zhu, Tan & Chatterjee, 2015, ApJ, sub.,
Planet Disk Interaction at the Dead Zone Inner Boundary



Inner, "Vulcan" Planet Mass versus Orbital Radius

$M_G = 5.0\ \phi_{G,0.3}\ \boldsymbol{\alpha}_{-3}\ r_{0.1AU}\ M_\oplus$

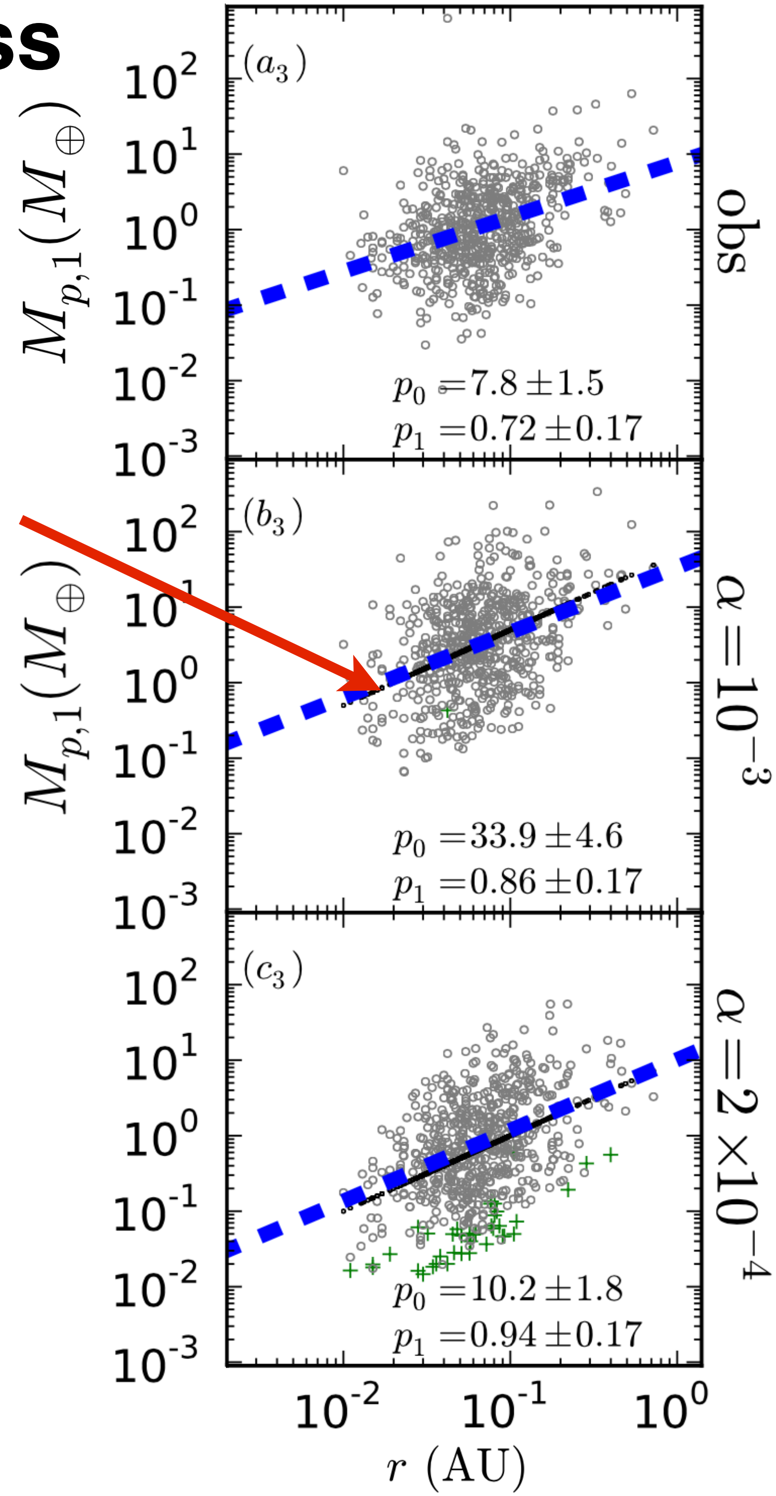
$$M_{p,1}/M_\oplus = p_0 r_{\rm AU}^{p_1}$$

Synthetic planet population with $M_G = 5.0\ \phi_{G,0.3}\ \boldsymbol{\alpha}_{-3}\ r_{0.1AU}\ M_\oplus$

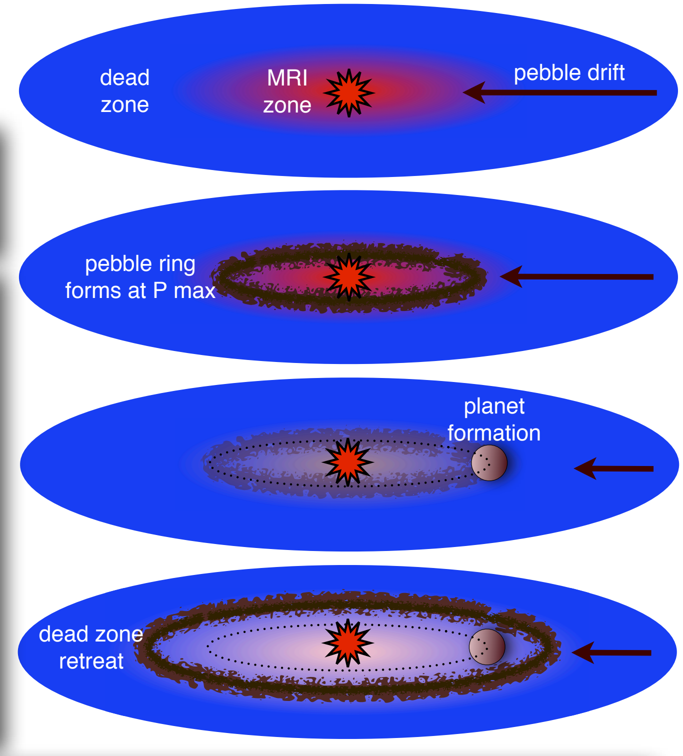
[include Kepler observational biases]

- Power law index, p_1, agrees
- Dispersion consistent with being due to density variations
- But normalization, p_0, too high

Consistent model if reduce DZIB viscosity:
$\boldsymbol{\alpha}_{-3} = 0.2$



Conclusions



Systems with Tightly-packed Inner (Super-Earth) Planets (STIPs) are common. Migration or In Situ Formation?

Inside-Out Planet Formation:

• Radial drift of cm-m sized solids

• Massive "pebble" ring at pressure maximum of dead zone inner boundary

• Planet formation & growth from pebble ring

• Planet mass grows until gap-opening

• Gap-opening leads to dead zone retreat

• New pebble ring forms, process repeats

Features of this planet formation model:

• Rapid radial drift of pebbles, i.e., meter-sized barrier, is not a problem for this model.

• Creates ~1-10$M_\oplus$ planets on tightly-packed close orbits, starting from typical disks.

• Predicts flat scalings of planet mass with orbital radius, consistent with observed systems.

• Orbital spacings should be ≥3 Hill radii of inner planet. Spacing from first to second planet should be larger than subsequent spacings, as observed.

• Inner "Vulcan" planet mass vs orbital radius $\mathbf{M_G = 5.0\ \phi_{G,0.3}\ \alpha_{-3}\ r_{0.1AU}\ M_\oplus}$, independent of accretion rate. Consistent with observed planets (both scaling and normalization).

How to stop STIP Inside-Out Planet Formation? (Solar System?)

• Outer pressure trap, e.g., due to opacity jump?

• Maintain MRI inner midplane region out to large radii - extra ionization due to radionuclides (^{26}Al)?

• Suppress MRI inner region (anti-aligned B-fields leading to Hall Effect suppression)?