# In Situ Accretion
# of
# Hot Neptunes and Super Earths

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# How are the small bodies distributed?

The first argument against the *in situ* formation of a planetary companion is based on models of the nebular disks[3] that are known to exist around young stars[4]. The standard picture of the formation of a giant planet involves the coagulation and accretion of small particles of ice and rock in the disk[5] until a core of about 15 Earth masses is built up; then gas, composed mainly of H and He, is accreted from the disk[6]. Standard disk models show that at 0.05 AU the temperature is about 2,000 K, too hot for the existence of any small solid particles. An alternative formation model[7] involves a massive disk, whose self-gravity is comparable to that of the central object, in which a gaseous subcondensation could form by contraction under its own gravity. But recent detailed calculations of such massive disks[8] indicate that they tend to form spiral arms and to transfer mass into the central star instead of fragmenting into subcondensations.

Lin, Bodenheimer & Richardson (1996) Nature, 380, 606

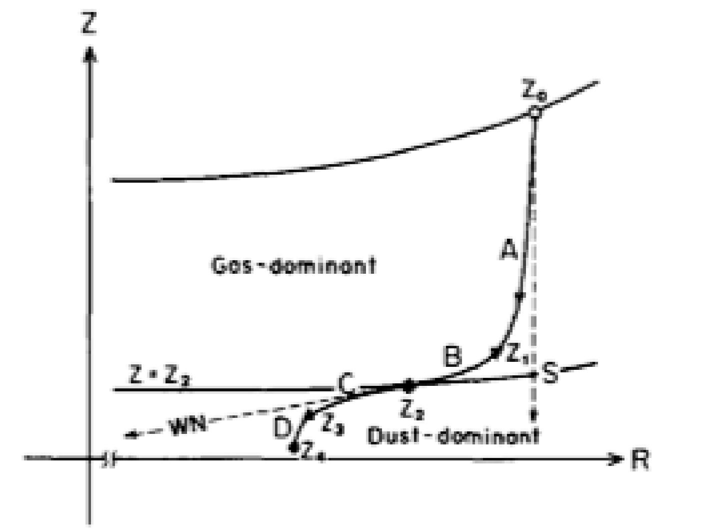



FIG. 1. A schematic illustration of the settling path in the *RZ* plane (solid curve). $Z_0$ (○) is the initial height and $Z_4$ (●) the final. $Z_2$ (◆) is the boundary height, dividing the settling process into the gas-dominant phase and the dust-dominant one. $Z_1$ (▼) and $Z_3$ (▲) are the heights of the turning points. The labels *A*, *B*, *C*, and *D* denote the settling phases from $Z_0$ to $Z_1$, from $Z_1$ to $Z_2$, from $Z_2$ to $Z_3$, and from $Z_3$ to $Z_4$, respectively. The dashed lines are the settling paths adopted in the previous studies by Safronov (S) and by Weidenschilling (W) and Nakagawa *et al.* (N).

Nakagawa, Sekiya & Hayashi (1986) Icarus, 67, 375

Plausible amounts of solid material interior to 1 AU amounts to about 20 Earth masses from a traditional nebula profile. But is this a reasonable assumption?

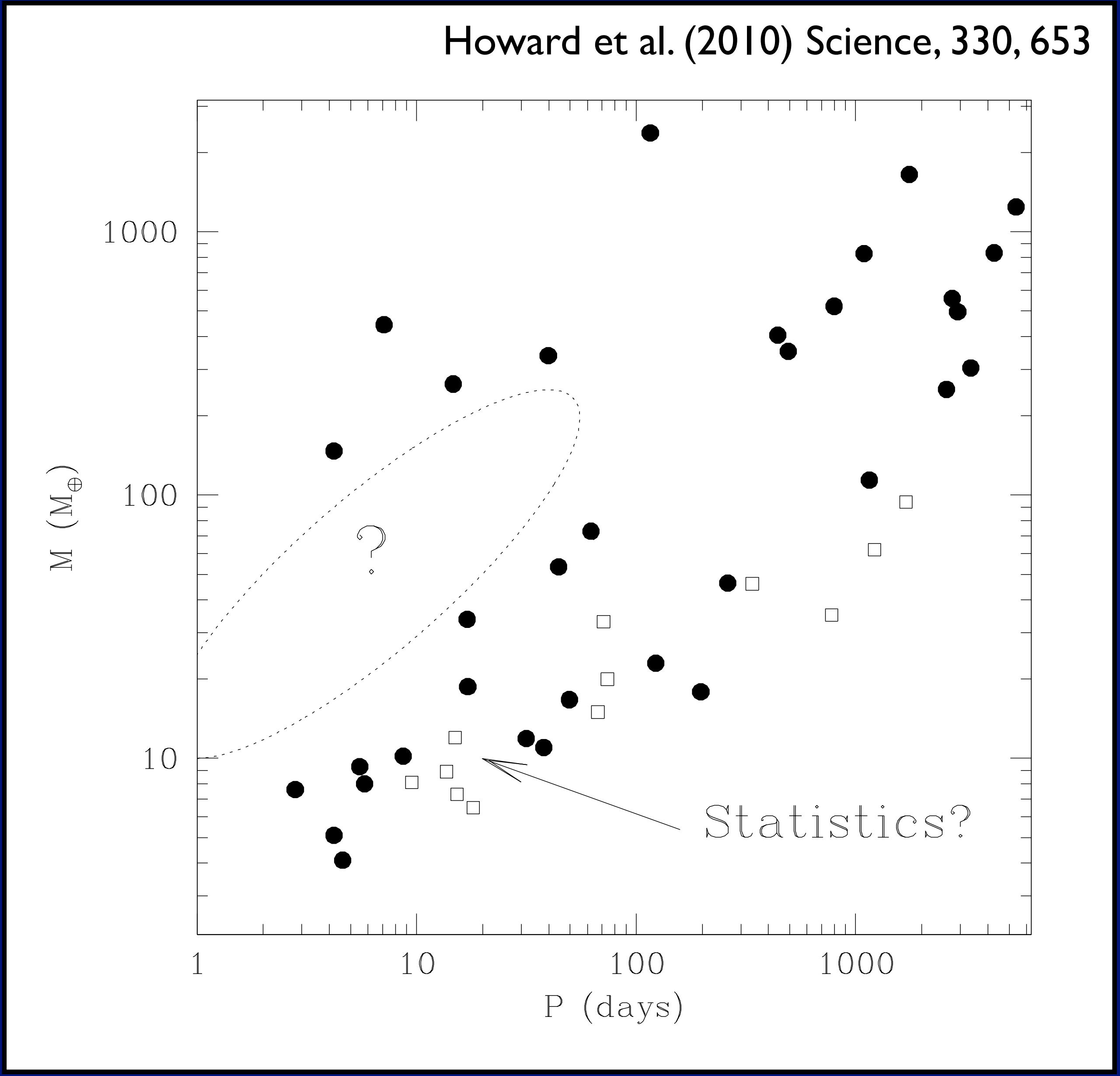
# Can some planets form in situ?/How much do we really need planetary migration?

Some puzzles to consider:

The origin of the gap between the Hot Jupiter and the Super-Earths

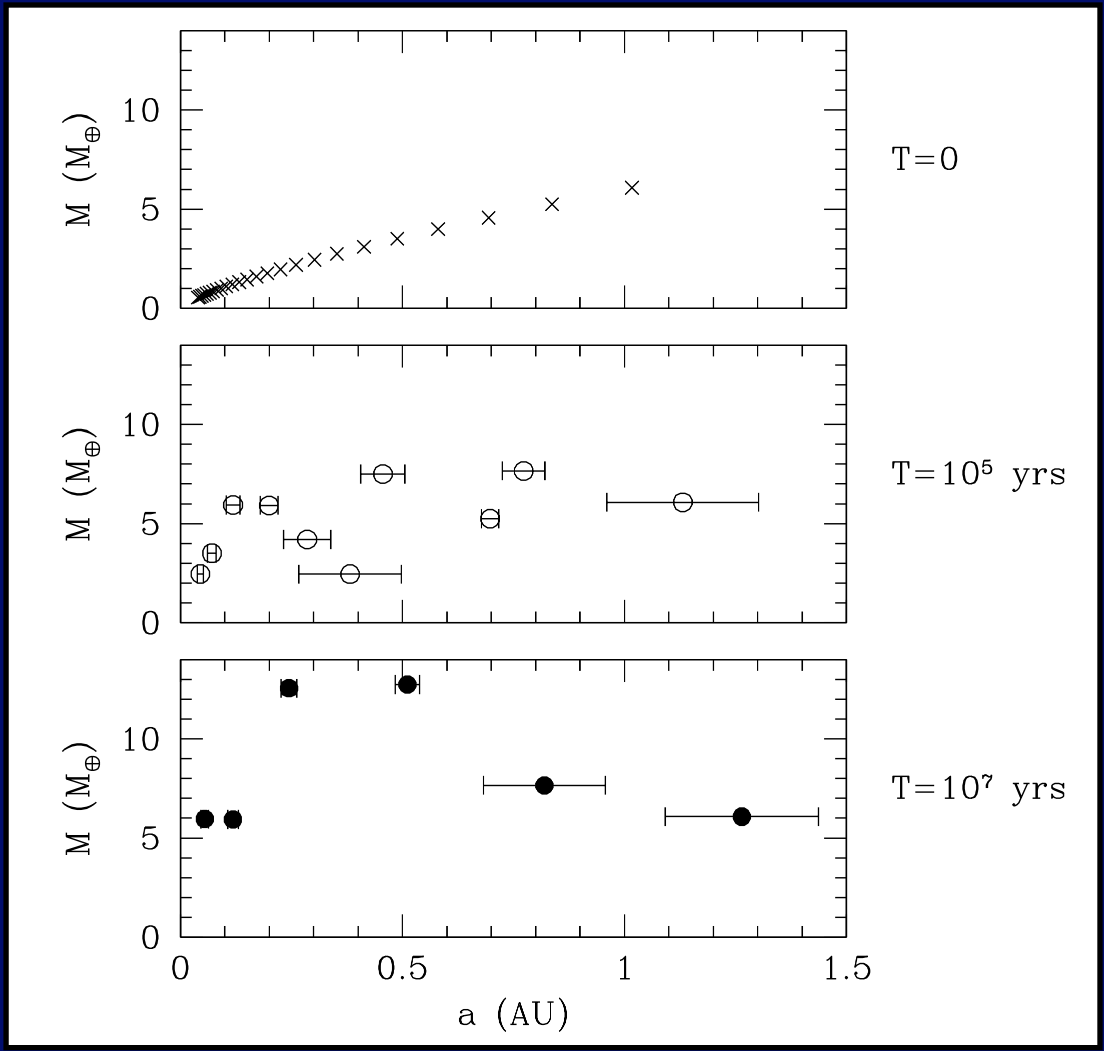
Statistics of Multi-planet systems

e.g. McNeil & Nelson (2010) MNRAS 401, 1691



# In situ assembly of large rocky planets

We have examined the assembly of rocky planetesimal disks of mass up to 100 $M_{\oplus}$, spread between 0.05 and 1 AU, for a variety of power law surface density distributions, $\Sigma \sim a^{-\alpha}$ .



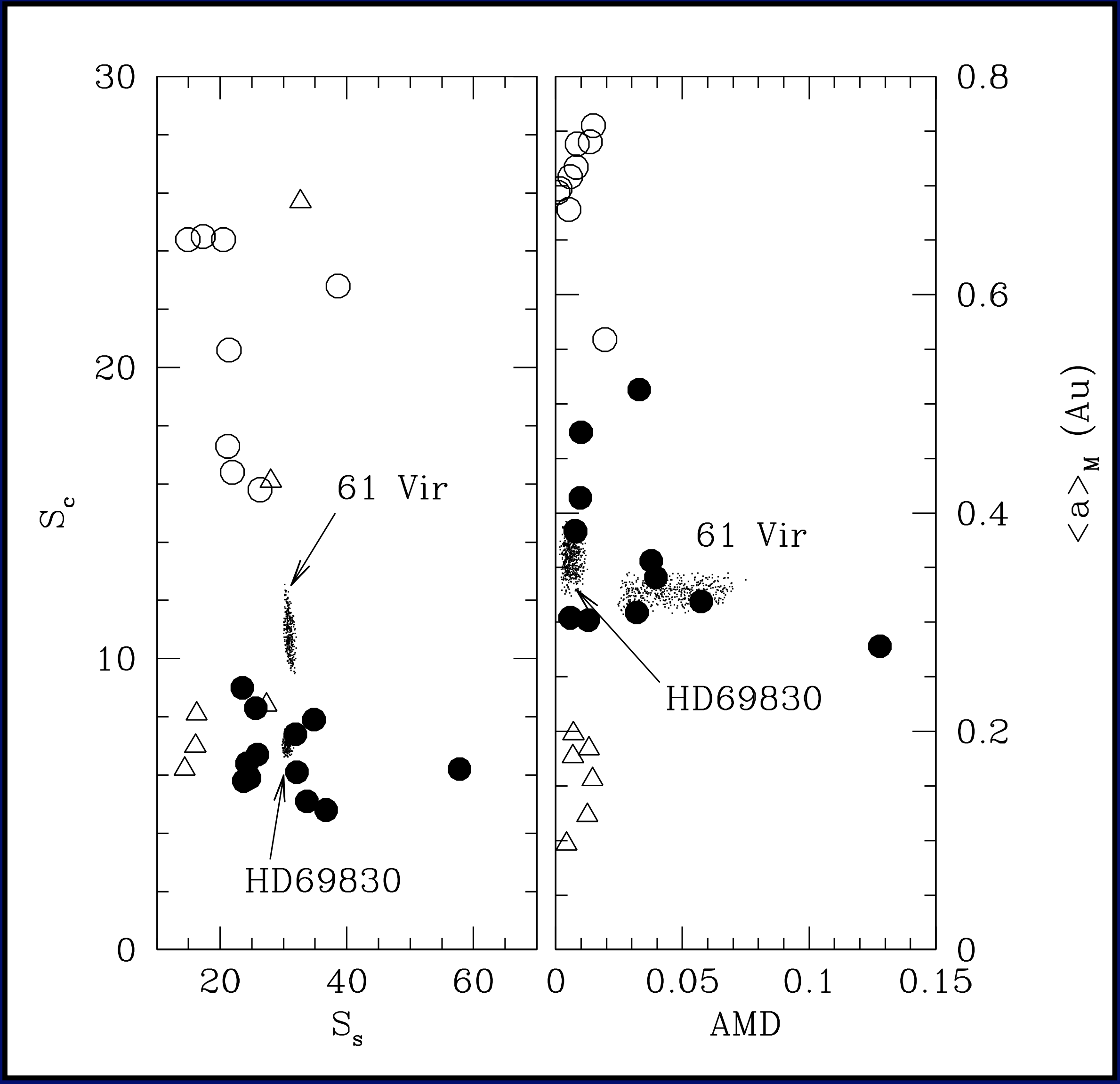

Initial masses were determined from the oligarchic model of Kokubo & Ida (1998) Icarus, 131, 171

Simulations were performed using the Mercury code (Chambers 1999, MNRAS 304, 793 )

# Known systems are consistent with in situ accretion

We focus on the two systems in Howard et al. which contain multiple systems of super earths, HD69830 and 61 Virginis.

Both systems can be matched by in situ accretion from a disk that resembles a scaled-up MMSN ($\alpha$=1.5, but M=50 $M_\oplus$)




Open circles and triangles represent shallower ($\alpha$ =0) and steeper ($\alpha$ =2.5) profiles.

# Accretion of Gas

To explain the observed masses, we need to form rocky cores of several to tens of earth masses. The collisional times in disks this massive are shorter than 1 Myr and these bodies are large enough to accrete gas from the nebula.

Accretion under such conditions is different from core accretion on larger scales (e.g. Rafikov 2006 ApJ 648, 666). The cores are large enough to open a gap in the gas disk before accreting to the level of giant planets.

If gas accretion is `tidally limited' in this fashion, it would provide a natural mechanism for the production of Neptune-mass objects with gaseous envelopes.

# Two classes of sub-Jupiter planet

Our simple in situ model can naturally produce both Neptune-class and Rocky planets. Whether a given planet accretes gas is determined by whether the core grows big enough to accrete gas before the nebula evaporates away.

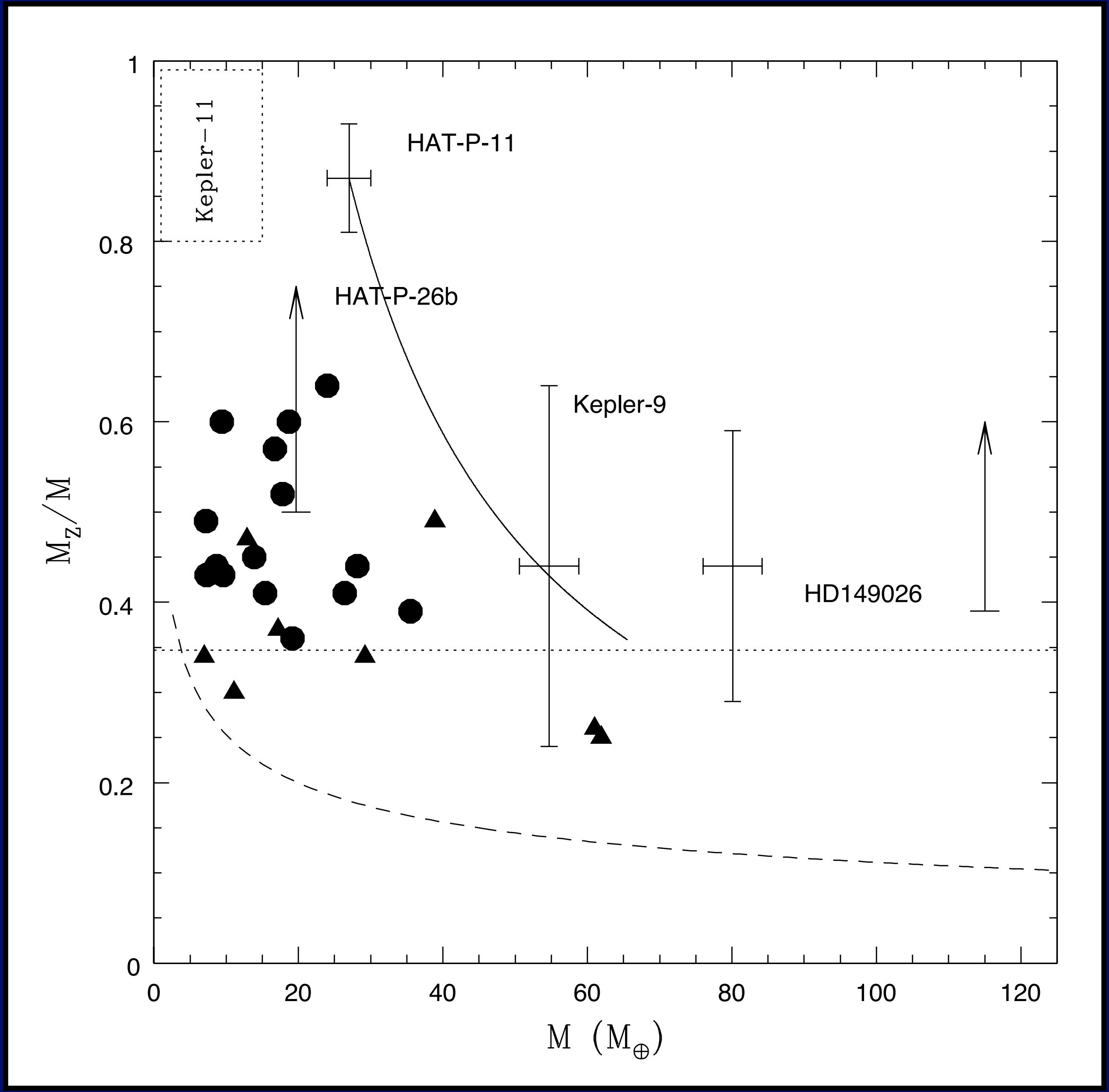
If we assume a nebular lifetime of 1 Myr, and a disk $\alpha=1.5$, we find an approximate threshold mass of 25 $M_{\oplus}$ for the rocky disk interior to 1 AU.

This dichotomy is supported by various analyses of the initial Kepler data release (Borucki et al. 2011 ApJ 736,19; Howard et al. 2011 ApJ 726, 73; Youdin 2011 arXiv:1105.1782; Lissauer et al. 2011 arXiv:1102.0543; Wolfgang & Laughlin arXiv:1108.5842)

# Nature of the Neptunes

Expected core ratios depend somewhat on the assumed gas disk, but  lie in the range of 30-60%, depending on the particular model.

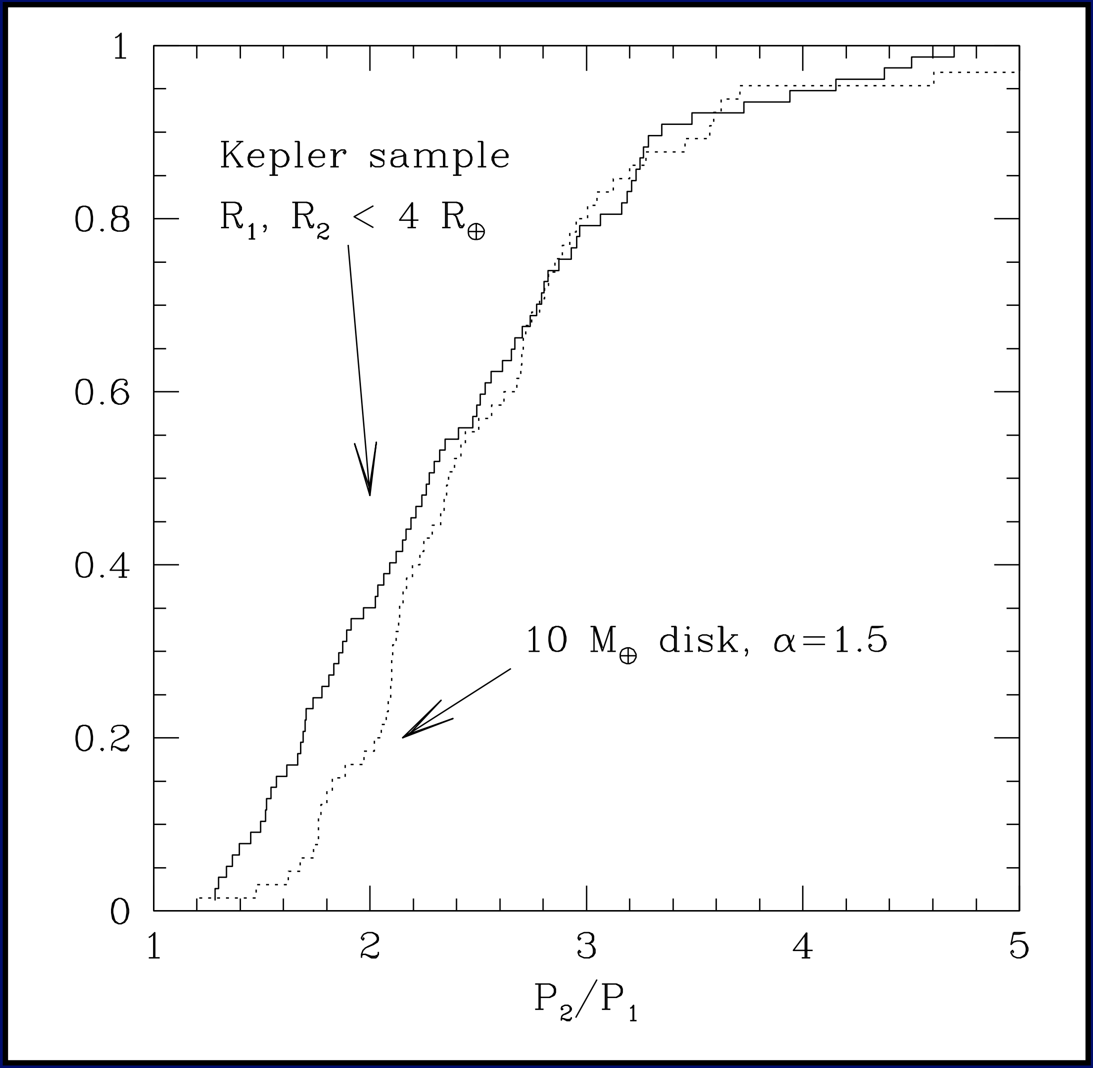
This is reasonably close to the observations.
(e.g. Havel et al. (2011) arXiv: 1103.6020 for Kepler-9 planets)



# Lower Mass Disks

Simulations to date have focussed largely on the higher masses, to match the observations of radial velocity surveys.

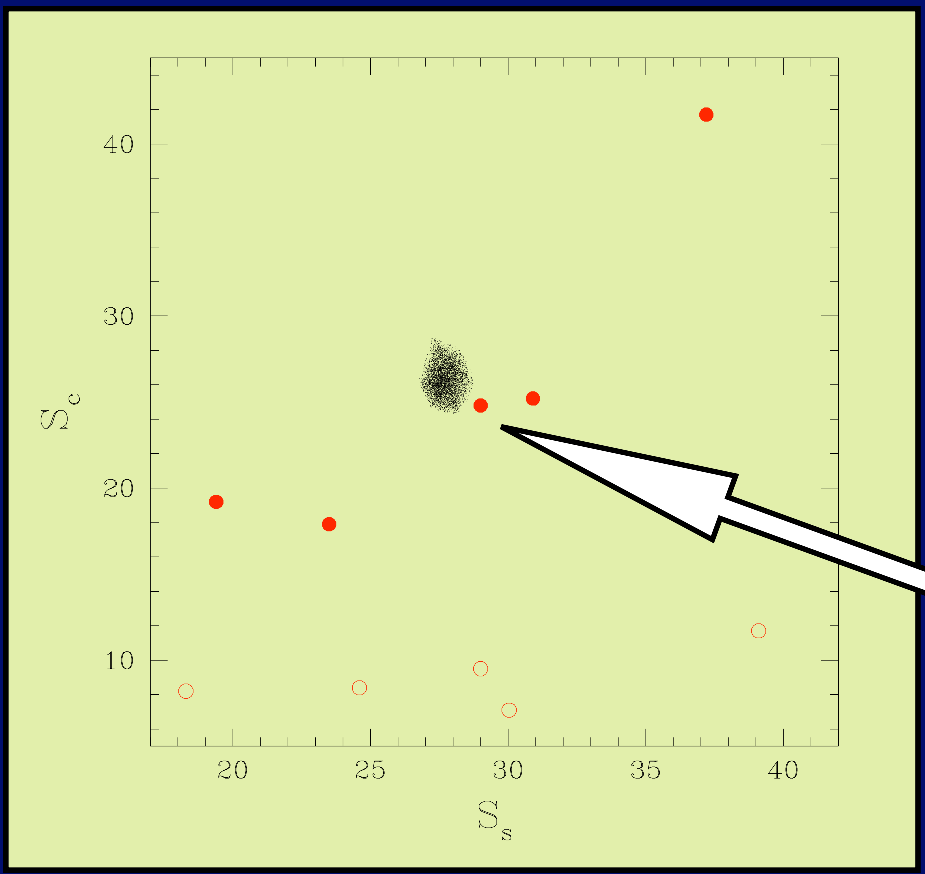
At lower masses, the properties of rocky planet systems from Kepler may also provide some interesting constraints.



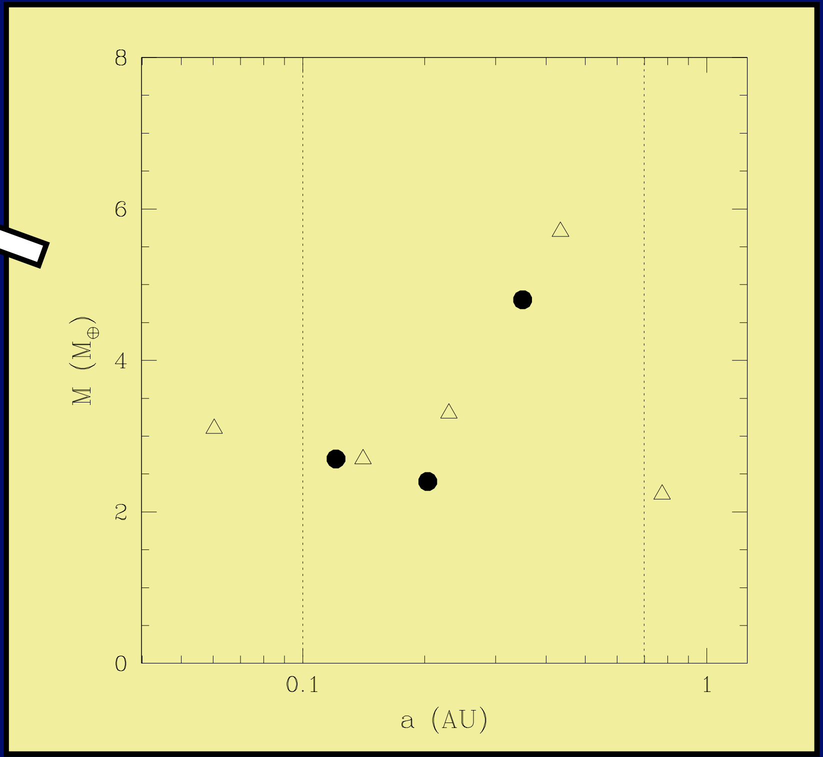

A preference for near-resonant systems is not solely the provice of migration models. In situ models show a pile-up outside 2:1

# HD20794 as an example of a rocky planet system

Pepe et al. (2011) arXiv: 1108.3447




Comparison with the results of a 20 $M_\oplus$, $\alpha$=1.5 disk shows good agreement if we restrict the comparison to 0.1<a<0.7



# Summary

In situ accretion is unlikely to be the full story in planet assembly, but it could very well play an important role.

Direct assembly of Neptune-mass planets in situ can reproduce the statistical distribution of observed multi-planet systems.

Tidally limited accretion of gas onto massive cores on sub-AU scales can provide a natural limiting mechanism for gas accretion, which can explain the truncation of mass at Neptune scales, and comparable rock/gas ratios.

We have also begun to examine lower mass disks, with an eye to comparing to the Kepler results. A pile-up near, but not in, resonances is also observed in these simulations.

# Supplement I

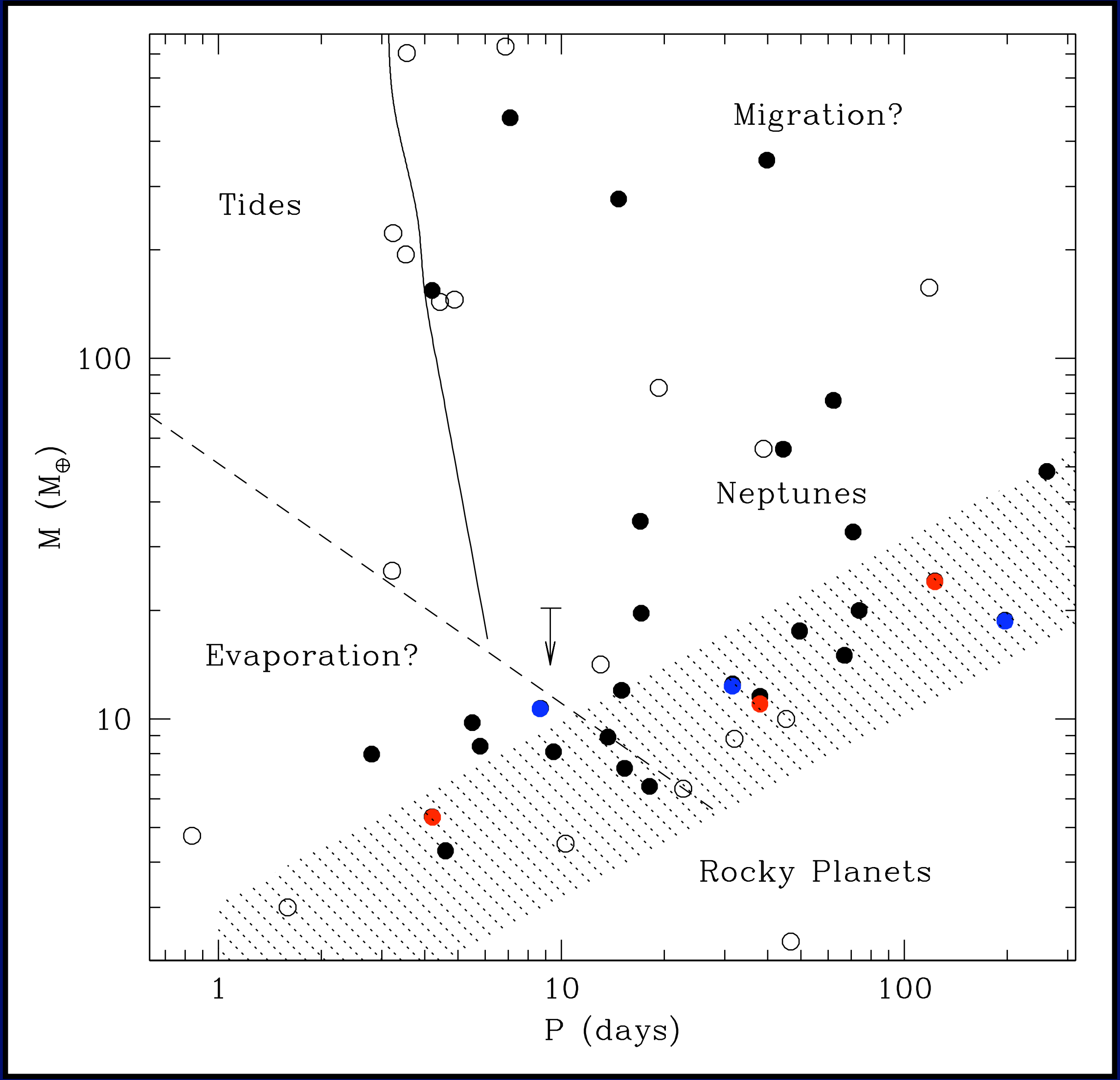
A guess as to the relevant processes in different regimes:

Jupiters inside 4 days can be tidally captured.

Neptunes & Rocky planets can be formed in situ

Low mass planets inside 10 days may lose gaseous envelopes

Jupiters at 10s of days are the puzzle - migration probably still needed

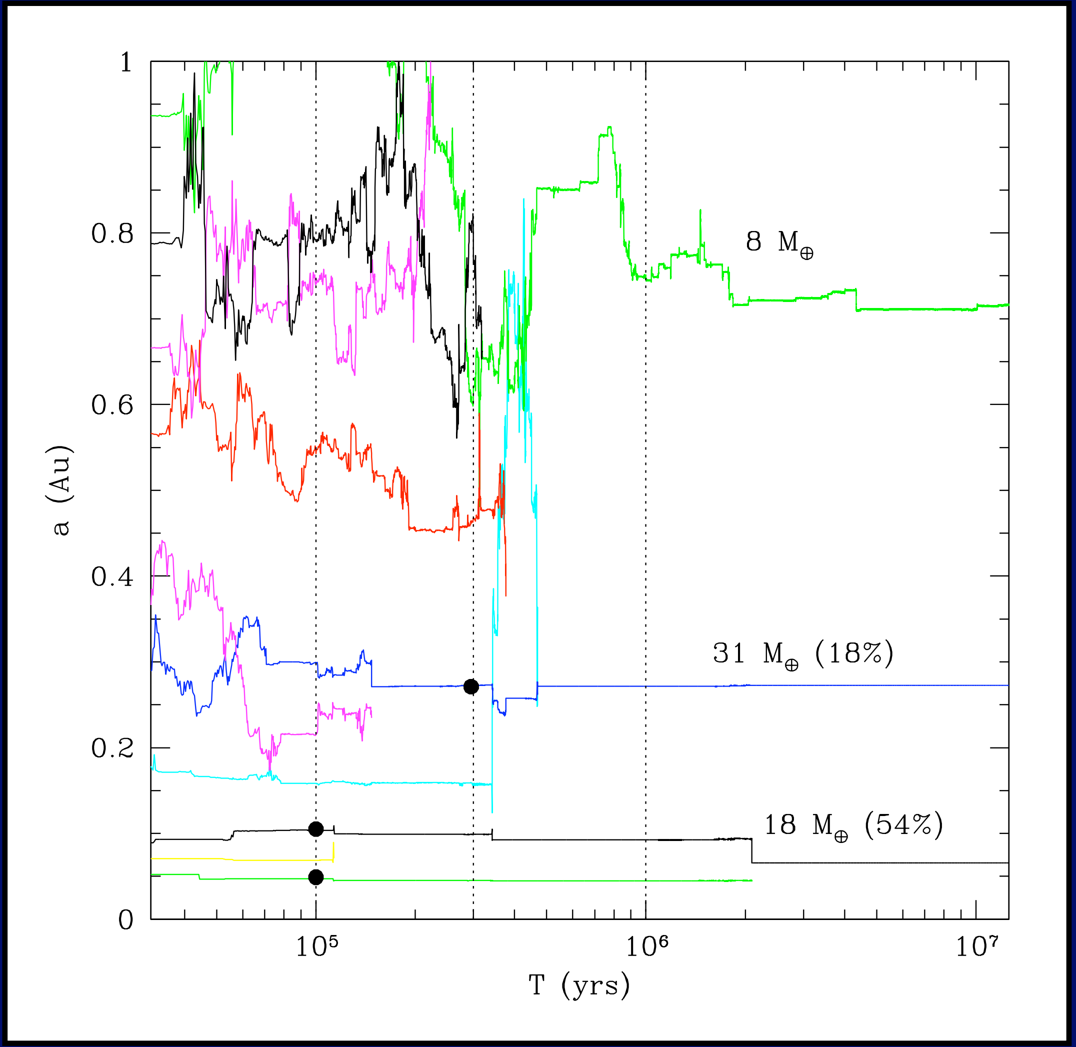


# Supplement II

An example of how we handle the accretion. We run an N-body simulation but stop at 1.e5, 3.e5 and 1.e6 years to see if any cores have exceeded the gas accretion threshold.

When a core does, the mass is increased to the new value and the simulation is restarted.

The simulation shown yields two hot Neptunes and one rocky planet further out.




The gas accretion episodes accelerate dynamical evolution. The innermost final body is actually a collision product of two proto-Neptunes.

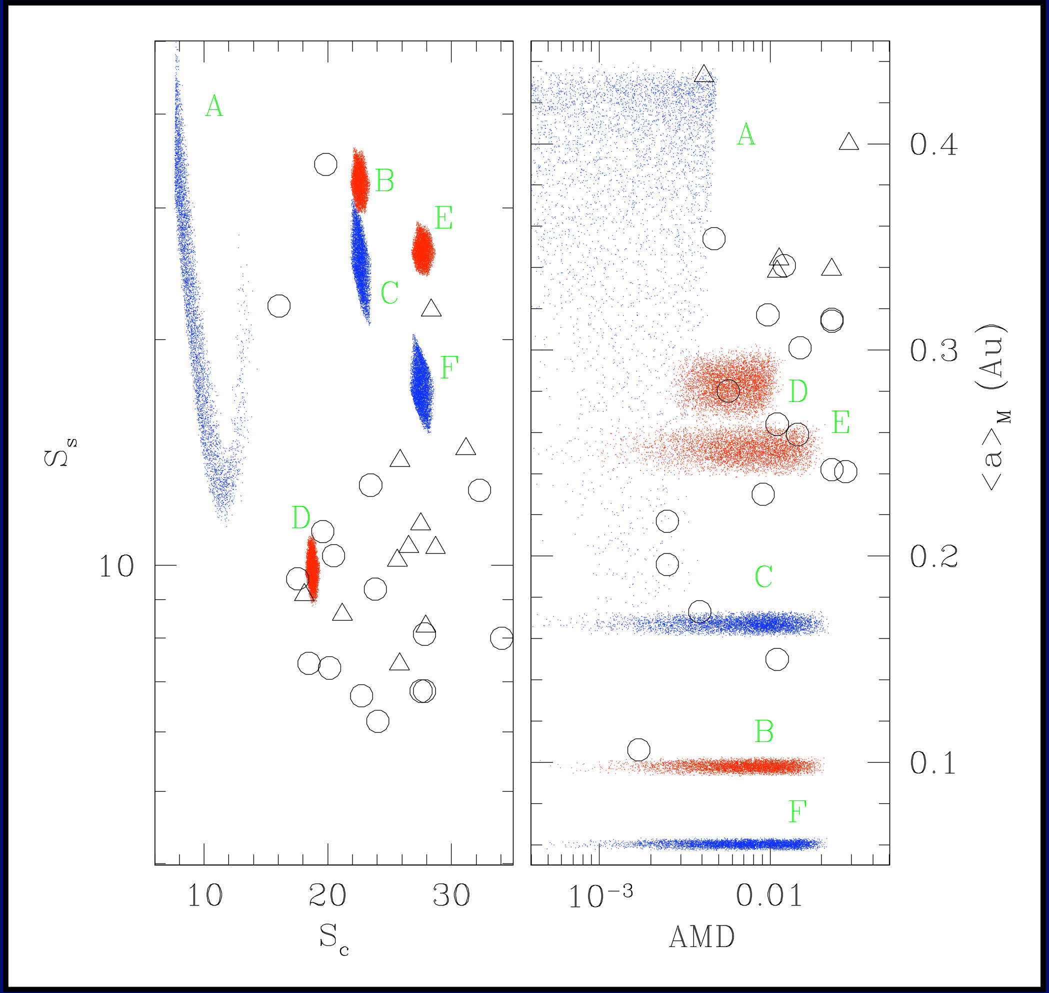
# Supplement III

Other known multi-planet systems in the same parameter space.

A = Kepler-11
B = HD 40307
C = Kepler-9
D = HD10180
E = HD20794
F = COROT-7

The 6 planet system HD10180 fits perfectly (only the 5 planets interior to 1 AU were used in calculating the statistics)

The uncertainties in Kepler-11 are due to the poorly constrained mass of the outer planet.




For orbits which were assumed to be circular, we allow random variation up to e=0.2

# Supplement IV

The definitions of the various statistics we have used:

$$AMD = \frac{\sum_j m_j \sqrt{a_j}\left[1 - \sqrt{(1-e_j^2)}\cos i_j\right]}{\sum_j m_j \sqrt{a_j}}$$

The angular momentum deficit measures deviations from circular, coplanar orbits

The mass-weighted semi-major axis tells us where most of the mass lies relative to the star

$$< a_M >= \frac{\sum_j a_j m_j}{\sum_j m_j},$$

$$S_c = max\left(\frac{\sum_j m_j}{\sum_j \left[\log_{10}(a/a_j)\right]^2}\right)$$

The mass concentration statistic, which measures how spread out or bunched the mass distribution is.

The orbital spacing statistic tells us how closely packed the system is, in terms of planetary gravitational influence

$$S_s = \frac{6}{N-1}\left(\frac{a_{max} - a_{min}}{a_{max} + a_{min}}\right)\left(\frac{3M_*}{2\bar{m}}\right)^{1/4}$$