Formation of Close-in Super-Earths and Mini-Neptunes

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KIT P Lunch Seminar
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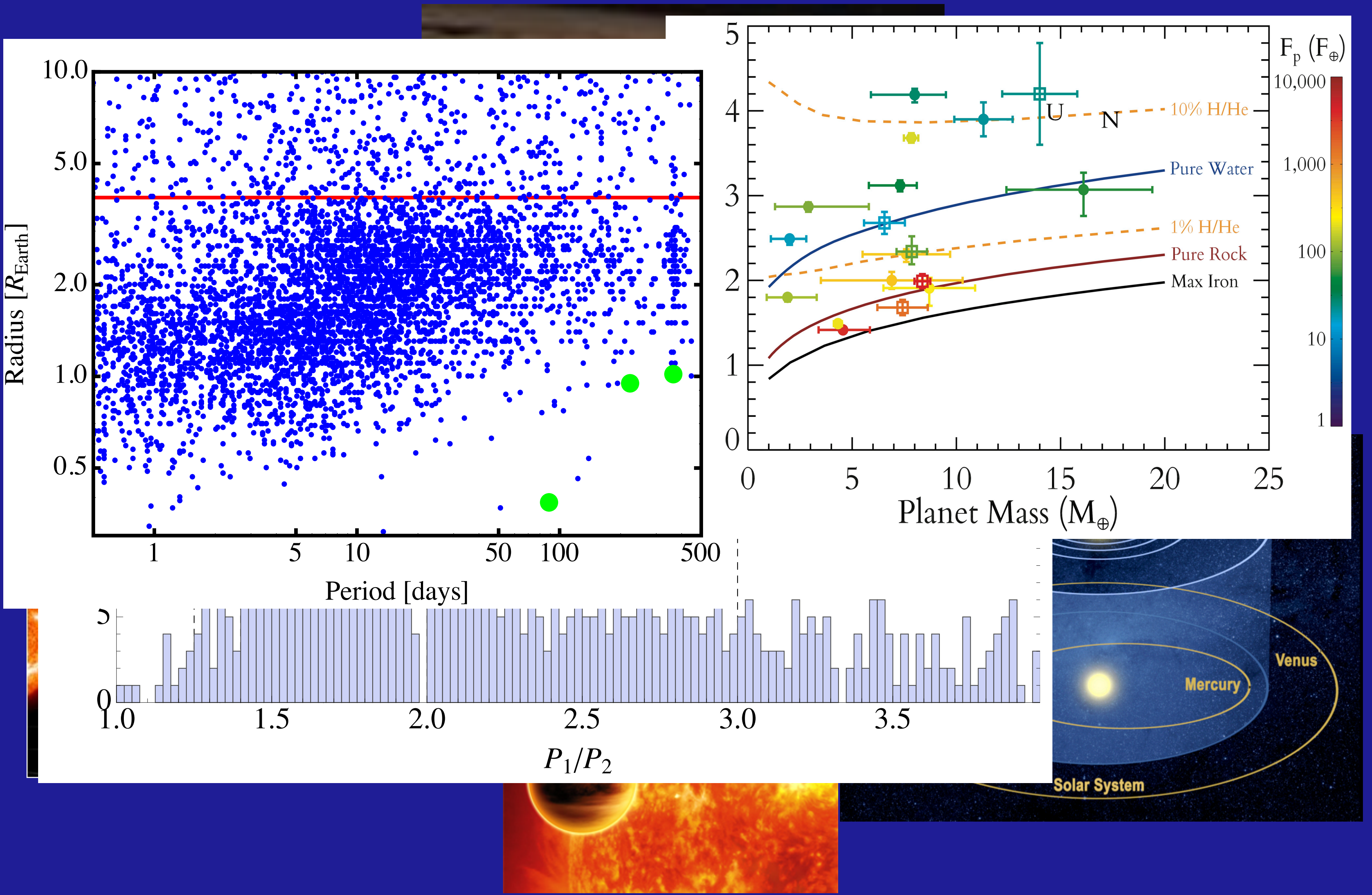
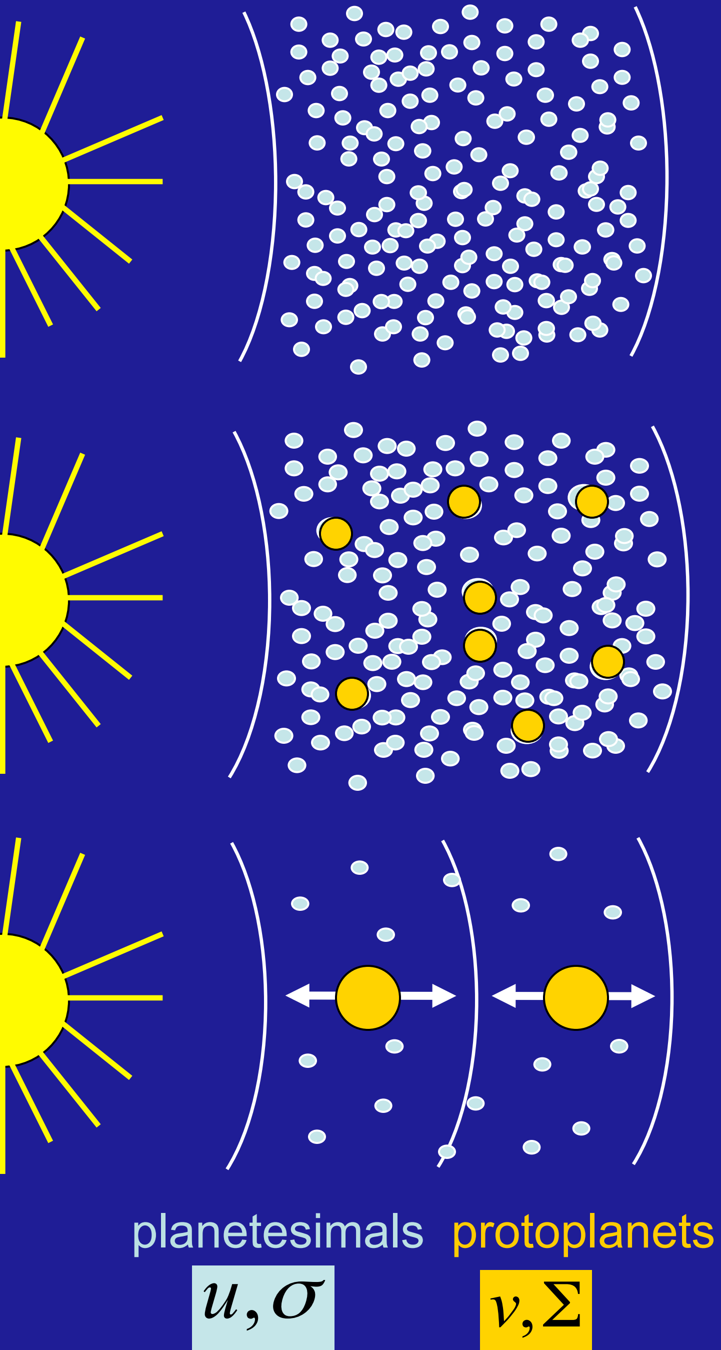
From Gas & Dust to Planets





1. Planetesimal formation:

2. Runaway growth:

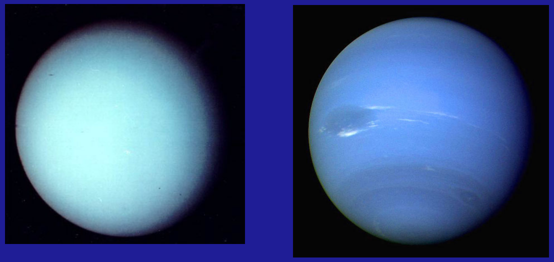
$$\frac{1}{R_1}\frac{dR_1}{dt} \propto R_1$$

For $v_{esc} > u$ gravitational focusing enhances the accretion rate

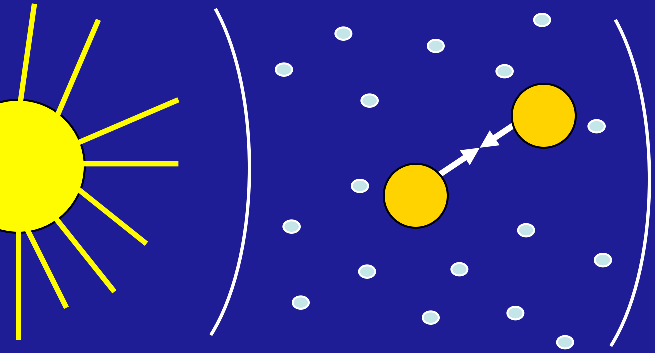
$$\frac{1}{R}\frac{dR}{dt} \sim \frac{\sigma\Omega}{\rho R}\left(\frac{v_{esc}}{u}\right)^2 \longrightarrow t_{grow} \sim 10^7 \text{ years}$$

3. Oligarchic growth & Isolation:

$$M_{iso} \approx 2\pi a(\Delta a_{zone})\Sigma \sim M_{Neptune}$$



Last Stages of Terrestrial Planet Formation

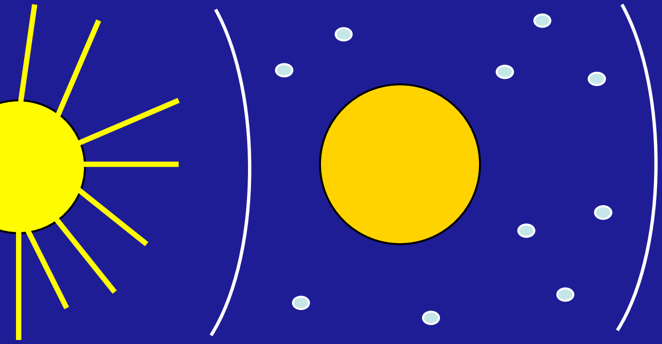


Giant Impacts:

Protoplanets’ velocity dispersion increases

⟶ Giant Impacts

$t_{\text{Giant-Impacts}}$ ~10^8 years (1AU)

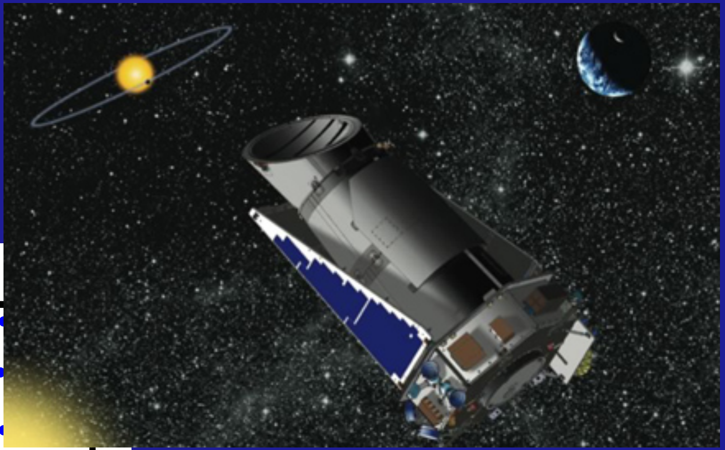


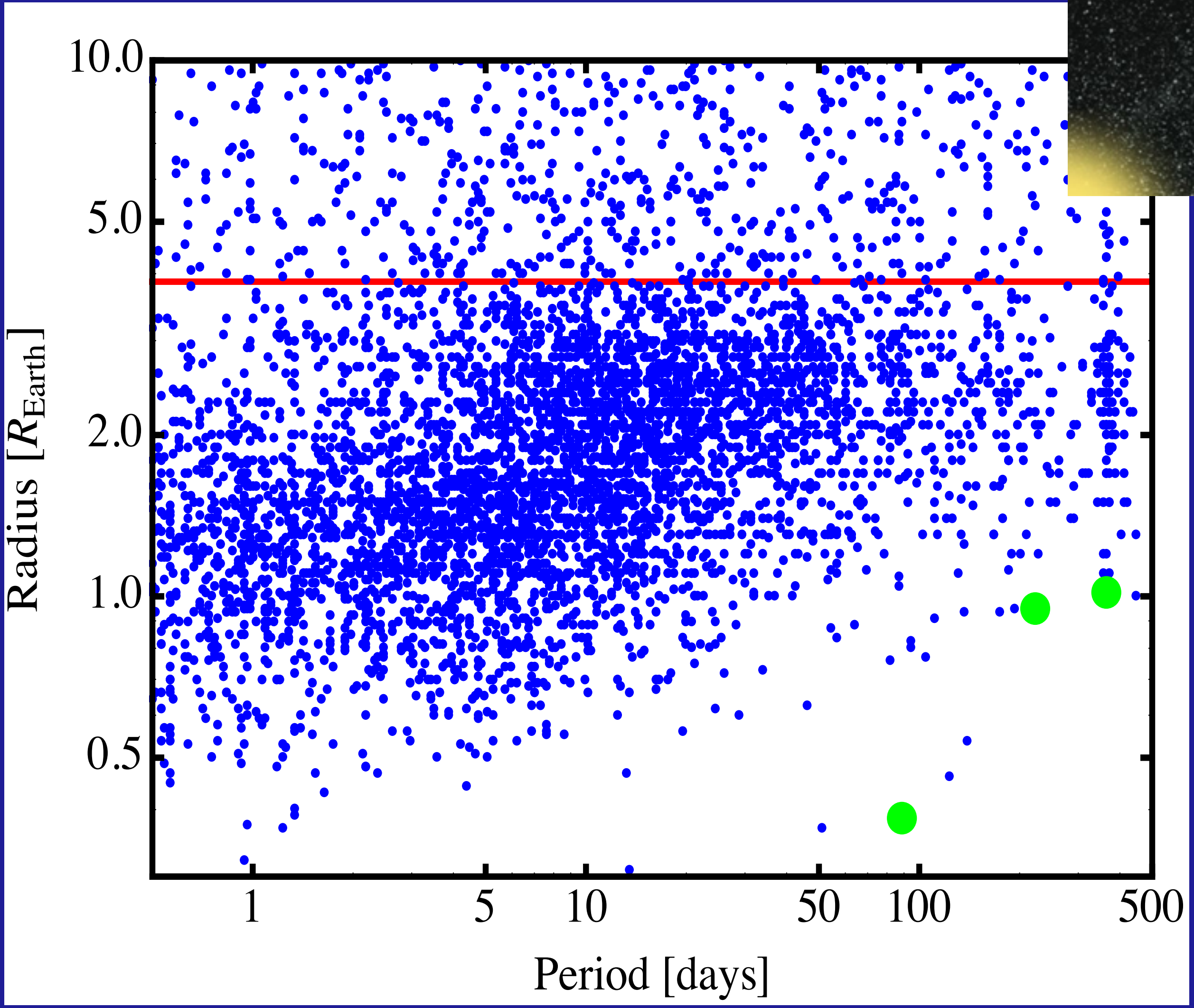
Clean up:

- Orbits planar & circular

- Accretion & ejection of remaining planetesimals

Kepler Mission





3538 Planetary Candidates

1218 Planets in Multi-Planet Systems

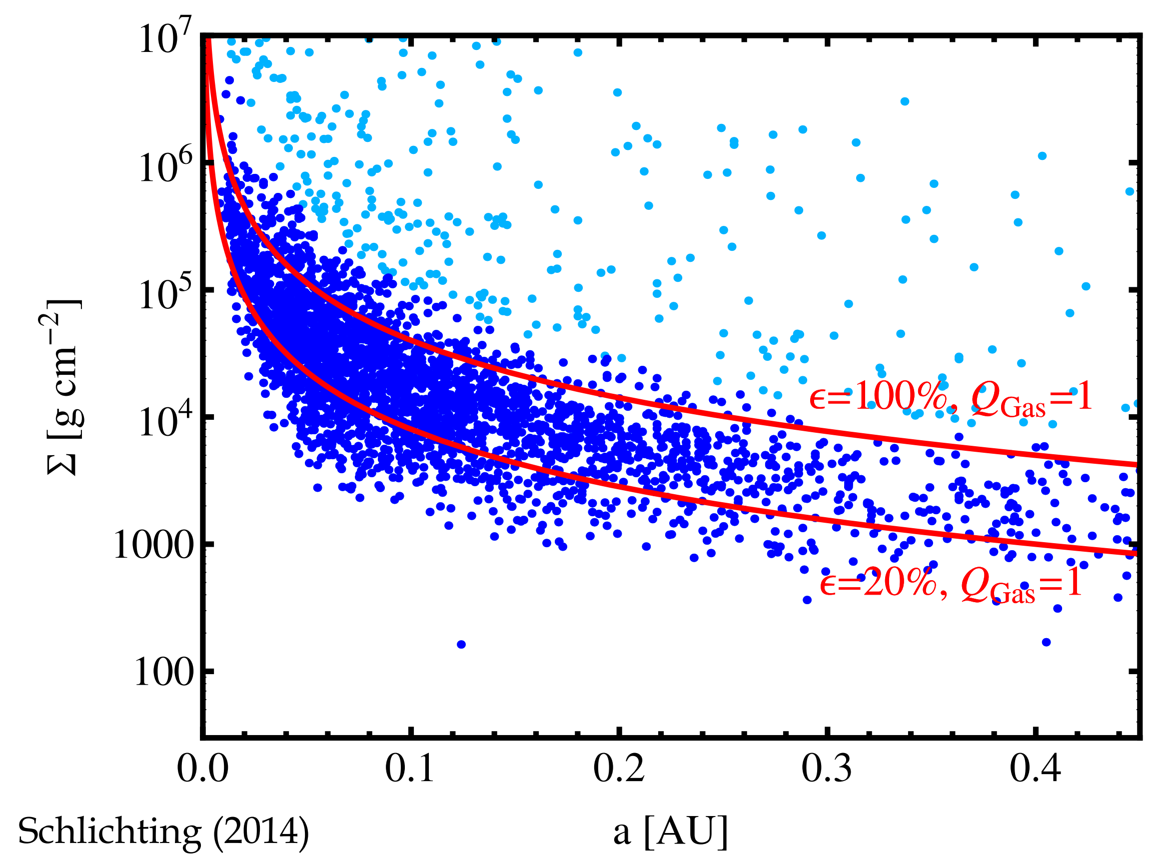
Medium Radius = 2.3 R_{Earth}
Medium Period = 9 days

All planetary candidates discovered by Kepler as of Nov. 5th 2013.

Part I

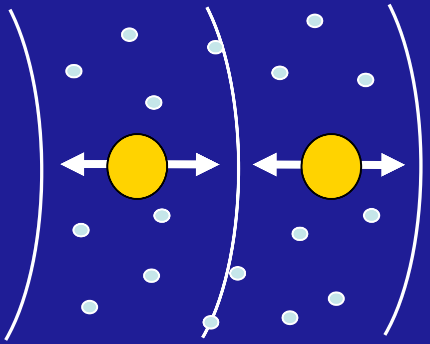
Materials & Supplies

Minimum Disk Masses Required



Schlichting (2014)

$$\Delta a \sim 2v_H / \Omega$$

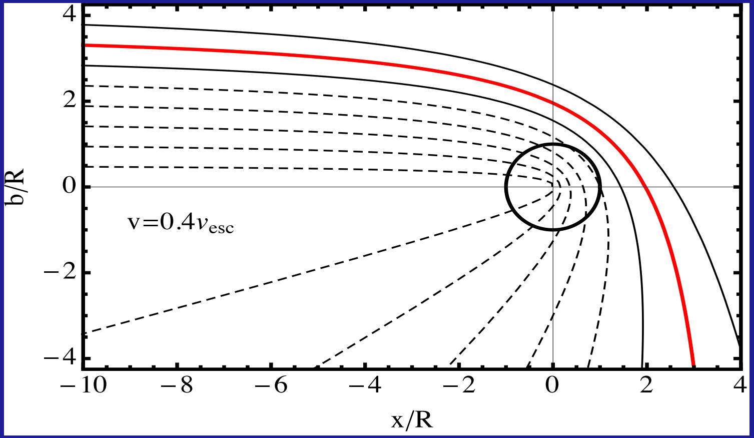


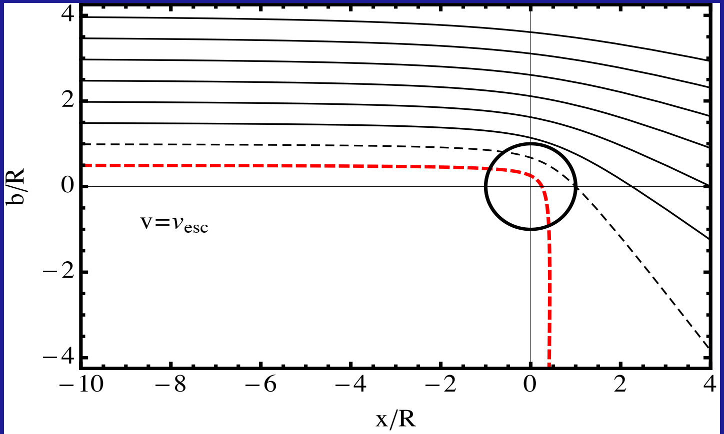
Viscous Stirring

Viscous stirring tends to increase the random kinetic energy all all bodies in the disk

For v <<v_{esc} $\sigma_{stirr} >> \sigma_{coll}$

For v >>v_{esc} $\sigma_{stirr} << \sigma_{coll}$

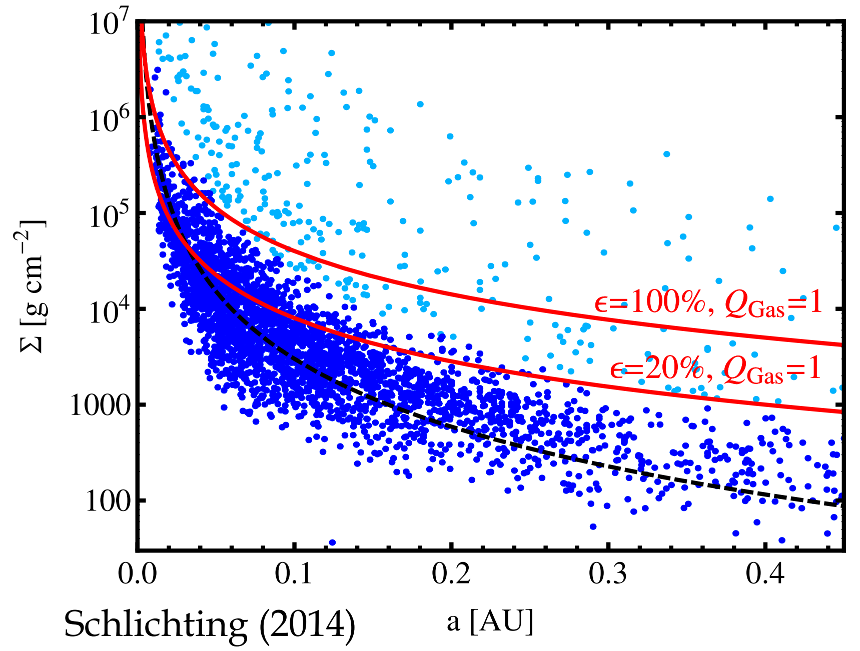




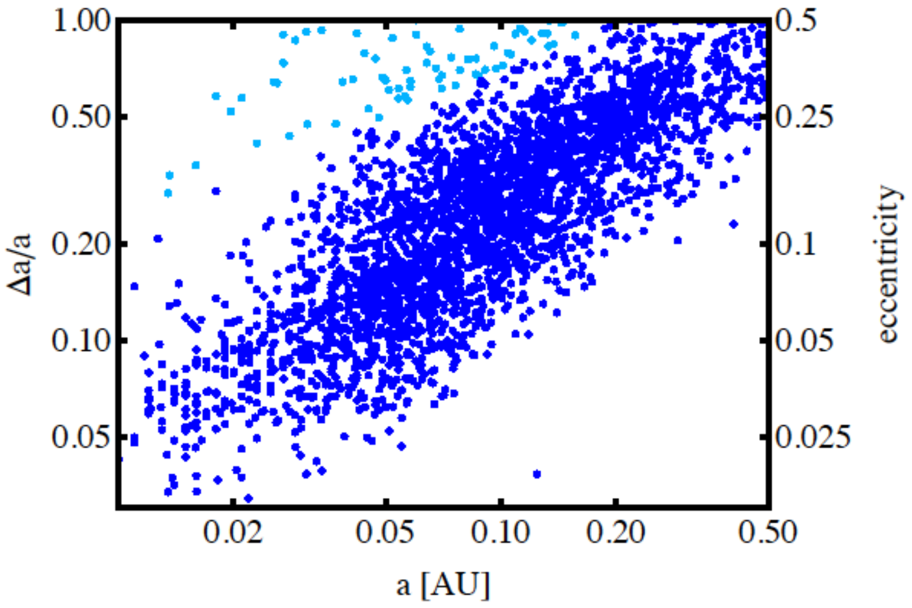
$$\sigma_{stirr} \sim \pi R^2 \left(\frac{v}{v_{esc}}\right)^{-4}$$

$$\sigma_{coll} \sim \pi R^2 \left(1 + \left(\frac{v}{v_{esc}}\right)^{-2}\right)$$

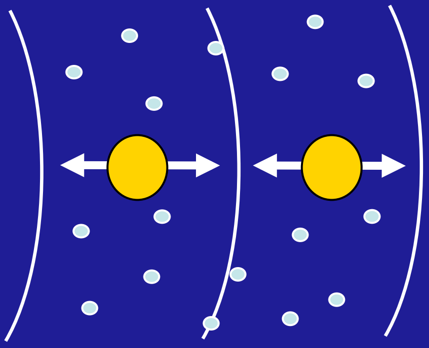
Minimum Disk Masses Required



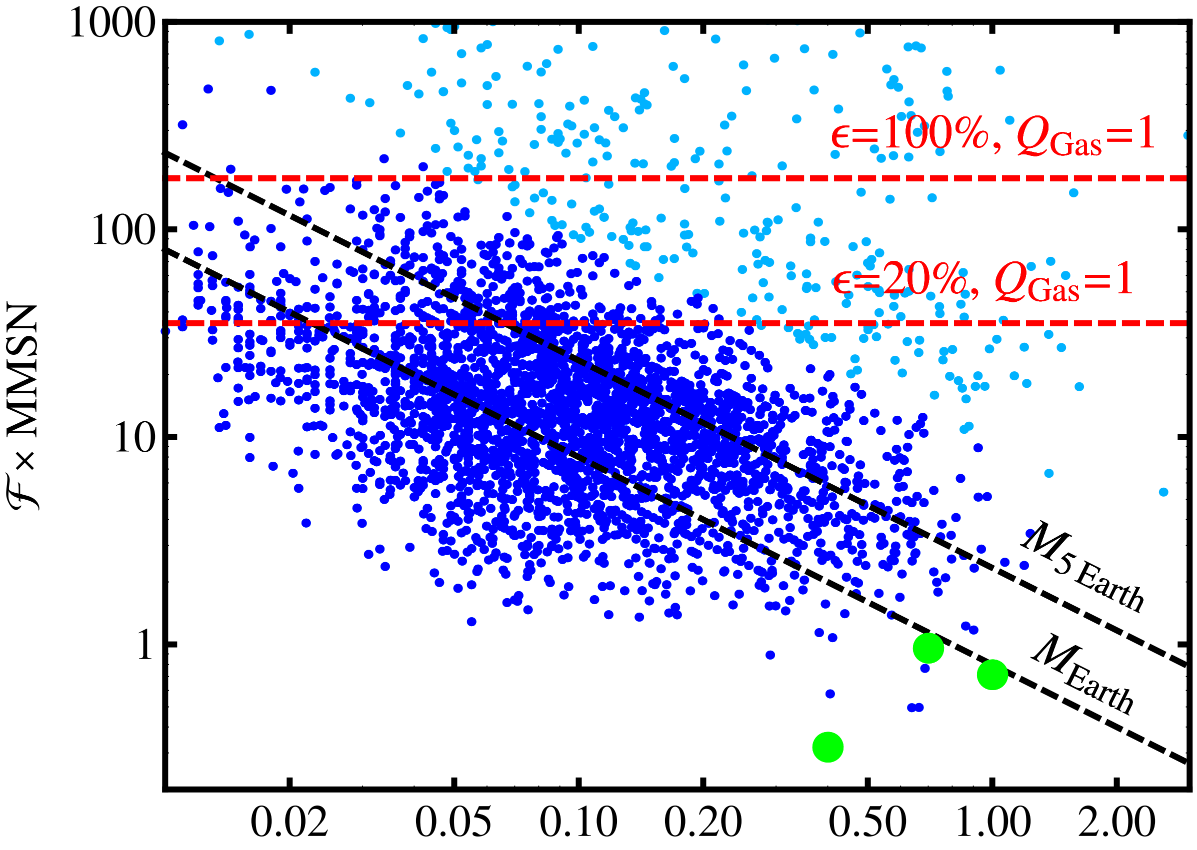
Schlichting (2014)



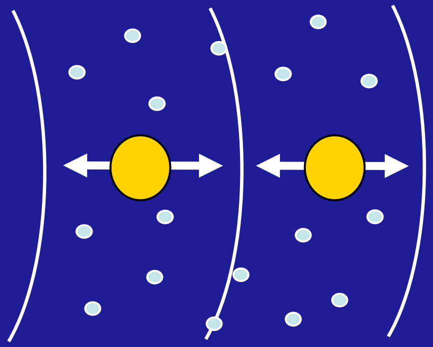
$$\Delta a \sim 2v_{esc} / \Omega$$



Minimum Disk Masses Required



Schlichting (2014)



$$M_{max} \simeq \frac{\left[2^{5/2}\pi a^2 \Sigma (\rho/\rho_\odot)^{1/6} (a/R_\odot)^{1/2}\right]^{3/2}}{M_\odot^{1/2}}.$$

Take Home Points I

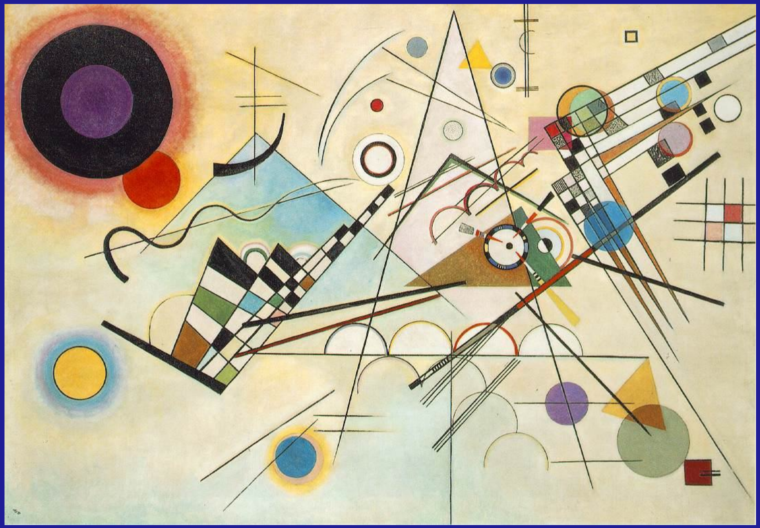
Formation of close in planets as isolation masses unlikely, need very massive inner disks and $\Sigma_{gas}/\Sigma_{dust} < 10$ for stability.

Formation of close in planets with Giant Impacts is a possibility, need massive inner disks, typically few tens MMSN.

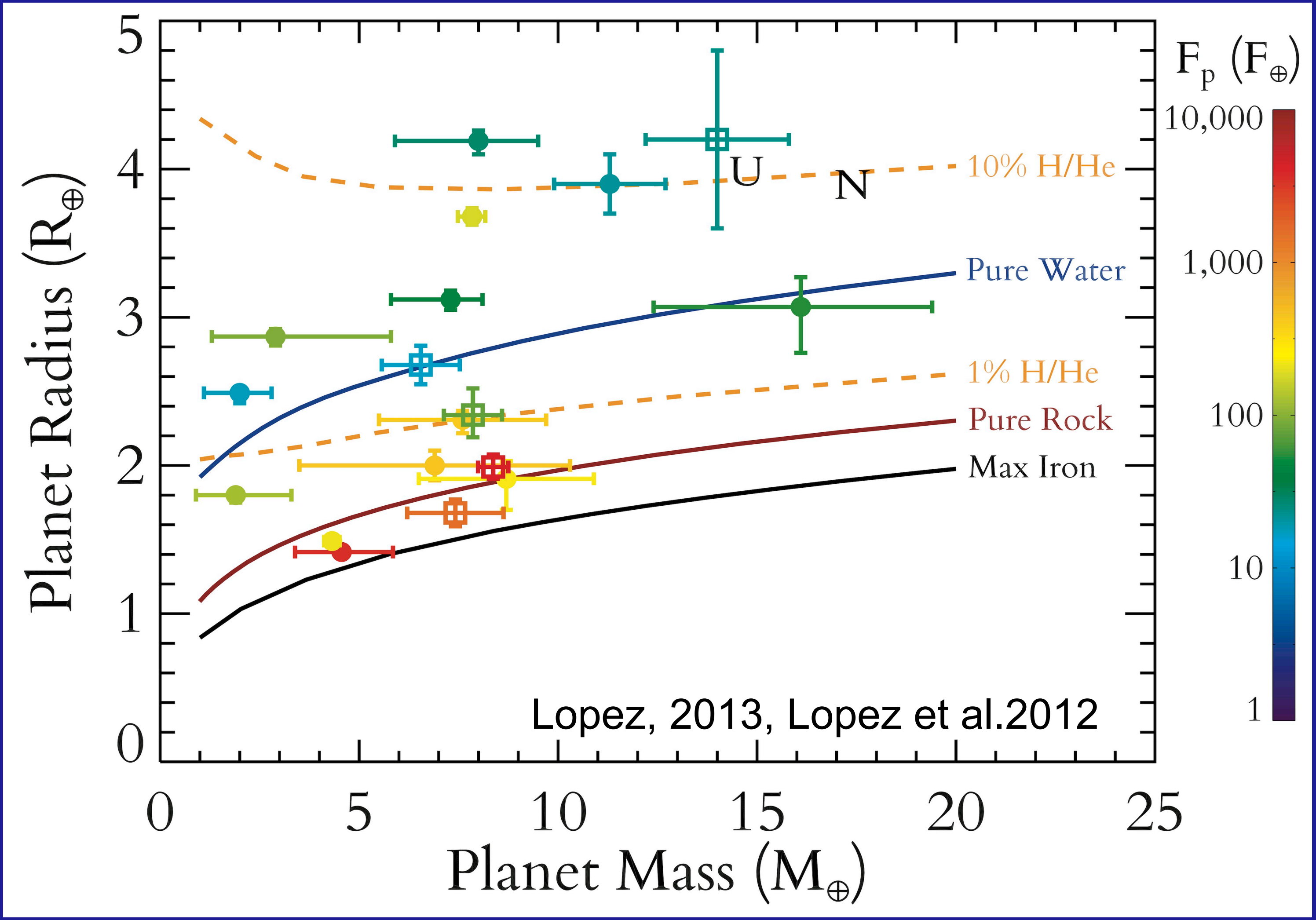
MMSN type disks fully consistent with formation further out and subsequent inward migration and/or radial inward drift of solids and subsequent local assembly.

Part II

Composition & Structure



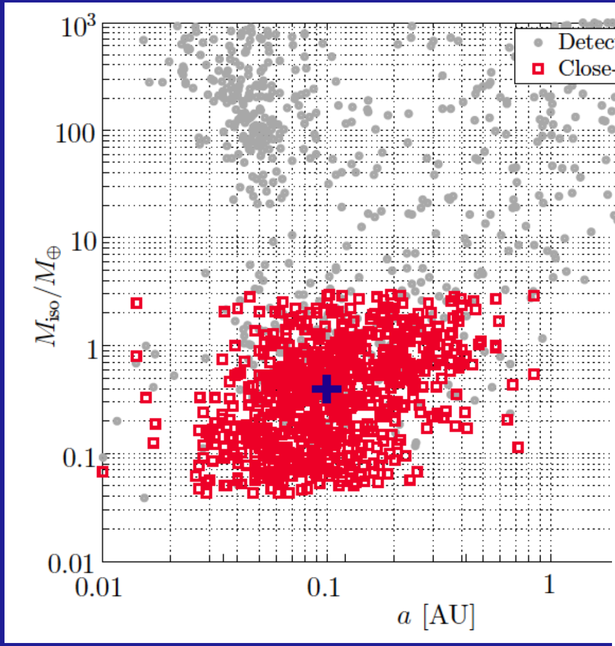
Exoplanet Atmospheres



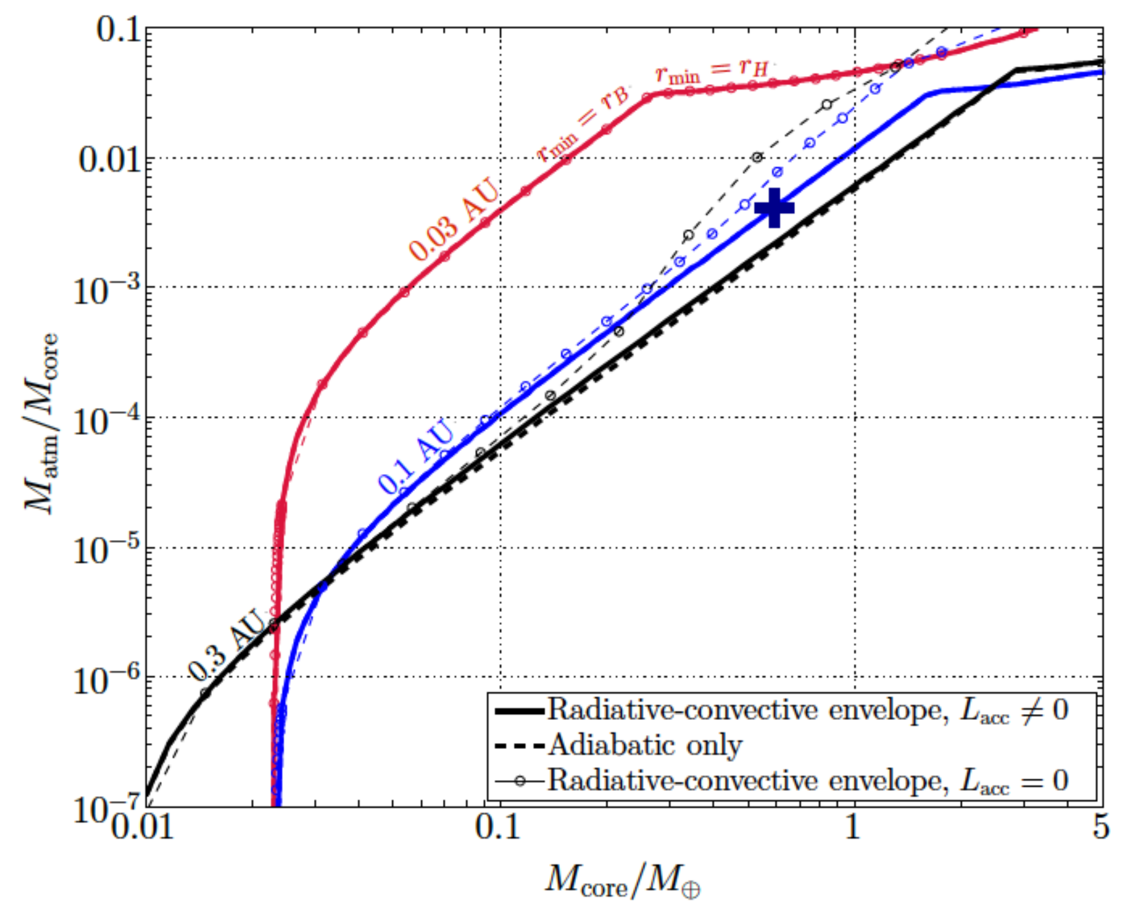
Lopez, 2013, Lopez et al.2012

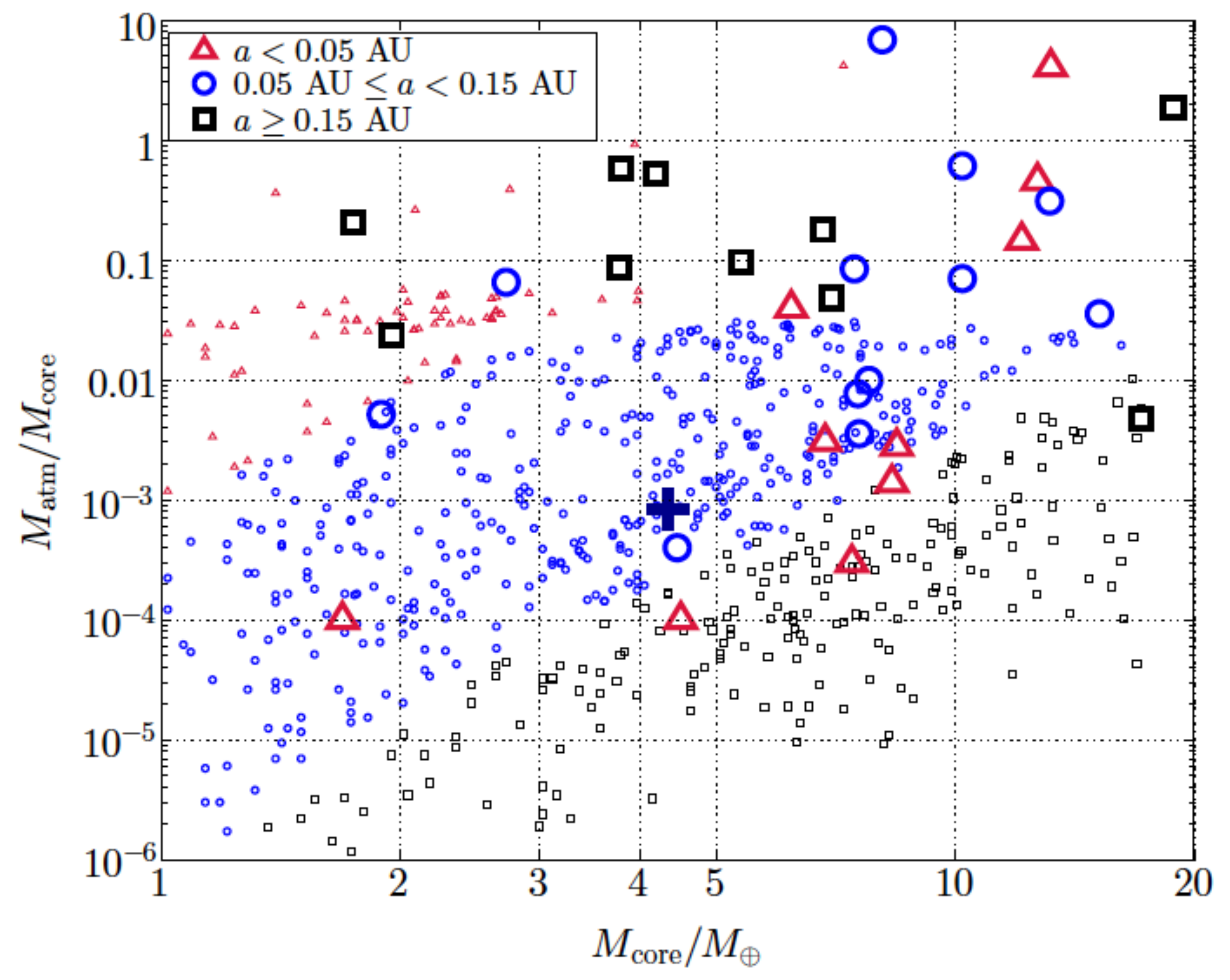
For comparison, the Earth's atmosphere contains less than 10^{-6} of its mass and has an atmospheric scale height that is only ~ 0.1% of its radius.

Atmospheres of Isolation Masses



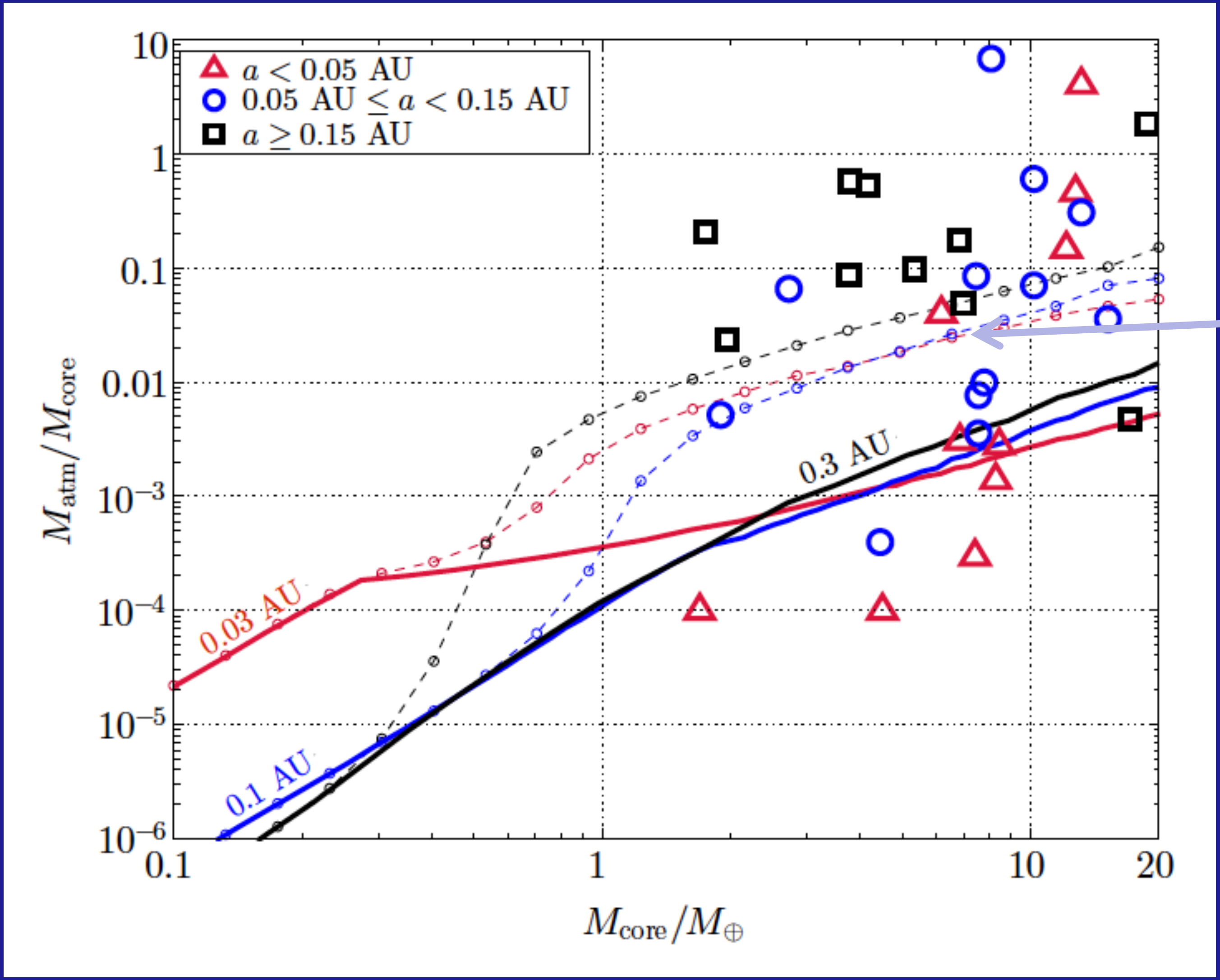
(Inamdar & Schlichting, 2015)





△ $a < 0.05$ AU
○ 0.05 AU $\leq a < 0.15$ AU
□ $a \geq 0.15$ AU
$M_{\rm atm}/M_{\rm core}$
$M_{\rm core}/M_\oplus$
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
2
3
4
5
10
20

Envelope Accretion After Giant Impacts

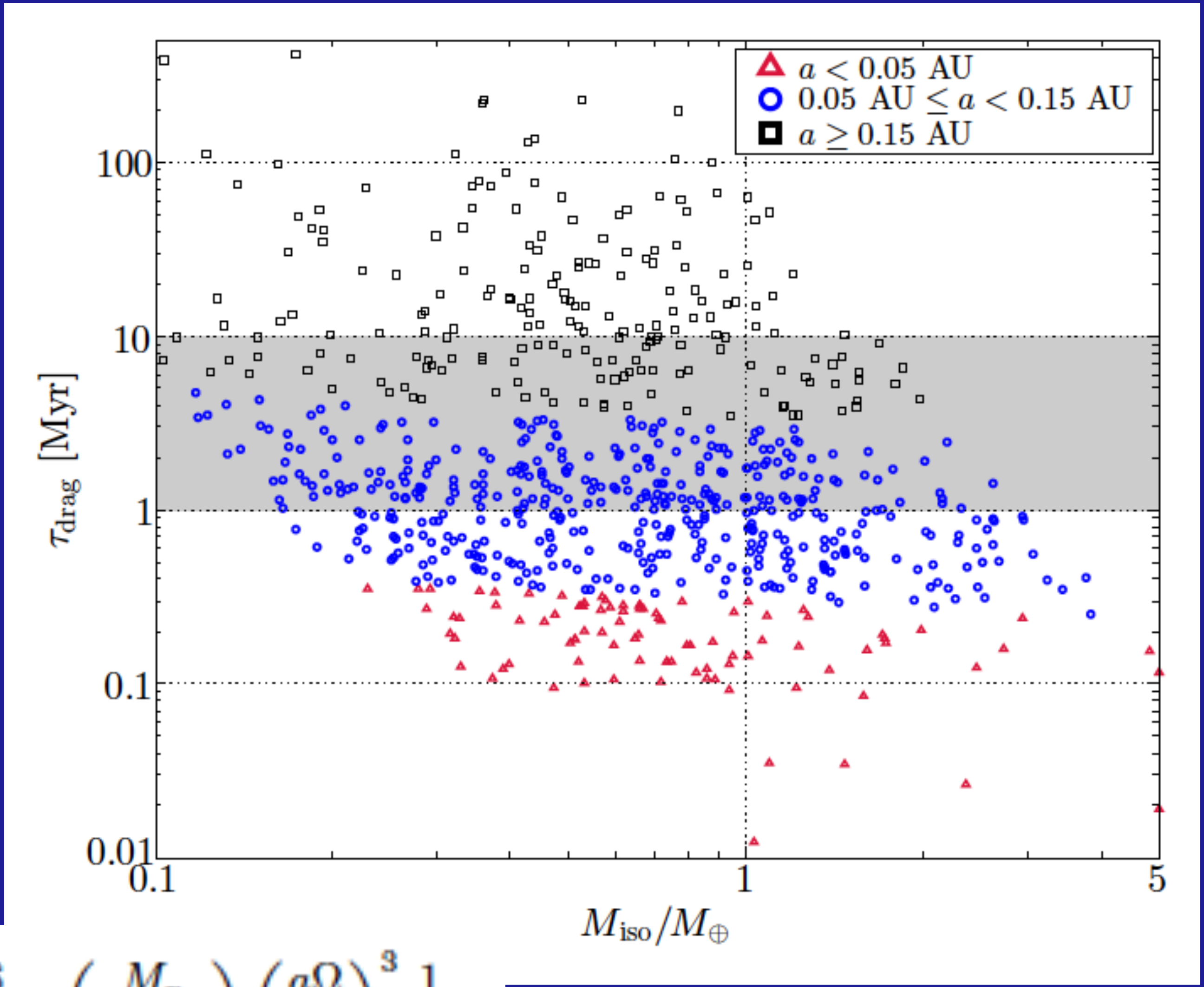


Symbols from Lopez & Fortney (2013)

L=0 (Lee, Chiang & Ormel 2014)

(Inamdar & Schlichting, 2015)

Radial Drift!



$R_{\rm core} \sim M^{1/4}$

$$\tau_{\rm drag} = \frac{16}{\pi C_D n^2}\left(\frac{M_p}{R_p^2\Sigma_g}\right)\left(\frac{a\Omega}{c_s}\right)^3\frac{1}{\Omega},$$

Take Home Points II

Formation of close in planets as isolation masses challenging, need very massive inner disks and $\Sigma_{gas}/\Sigma_{dust} < 10$ for stability and to prevent run-away gas accretion (Lee et al. 2014).

Formation of close in planets with Giant Impacts is a possibility for atmospheres of few % and less if: 1) $L_{acc}=0$, 2) have massive inner disks, typically few tens MMSN and 3) $\Sigma_{gas}/\Sigma_{dust} < 10$ to prevent radial drift.

Formation models of close in planets need to account for radial drift of solids and/or migration.