Terrestrial Planet Formation: A Blueprint for the Formation of Close-in Super-Earths and Mini-Neptunes?

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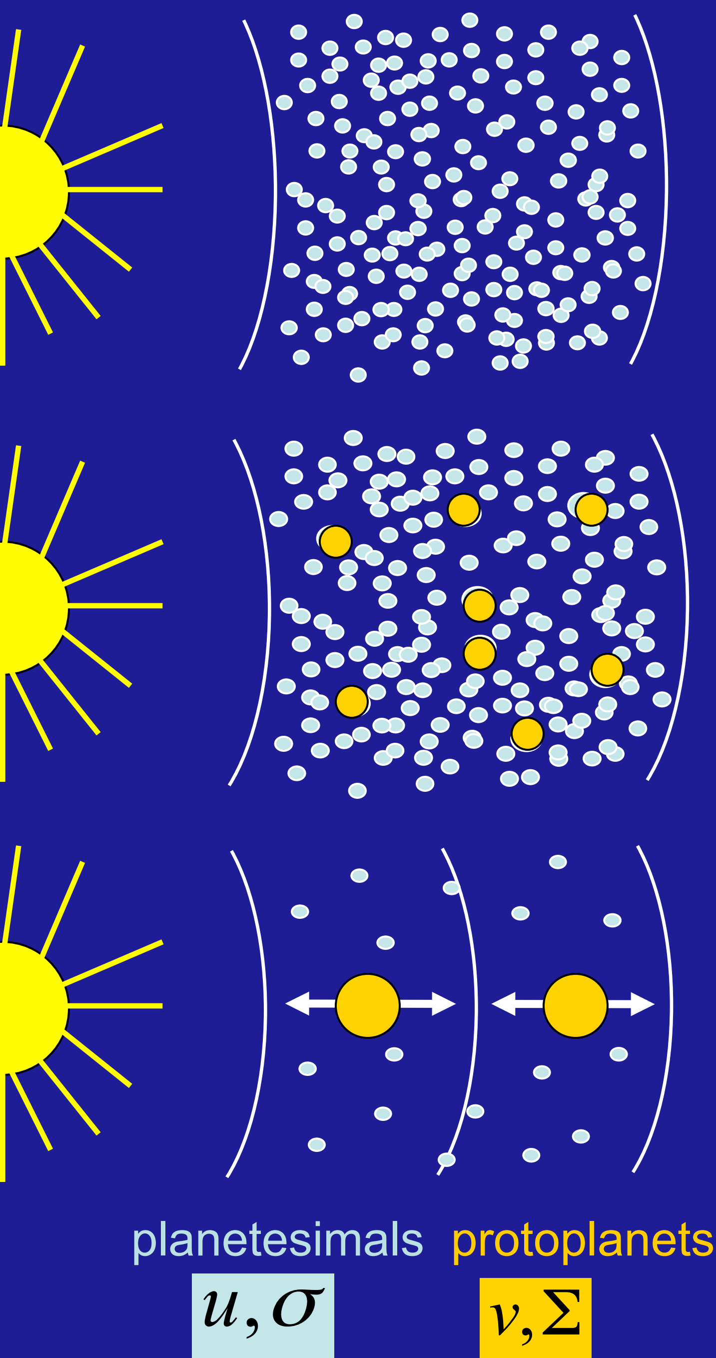
Physics of Exoplanets: From Earth-sized to Mini-Neptunes

KITP

Feb 27th 2015



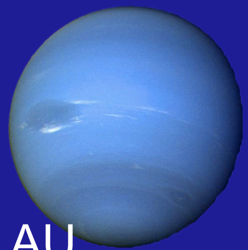
1. Planetesimal formation:

2. Runaway growth:

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

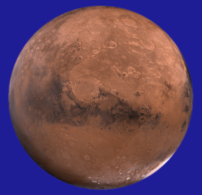
$$\frac{1}{R}\frac{dR}{dt} \sim \frac{\sigma\Omega}{\rho R}\left(\frac{v_{esc}}{u}\right)^2 \longrightarrow t_{grow} \sim 10^7 \text{ years}$$

3. Oligarchic growth & Isolation:

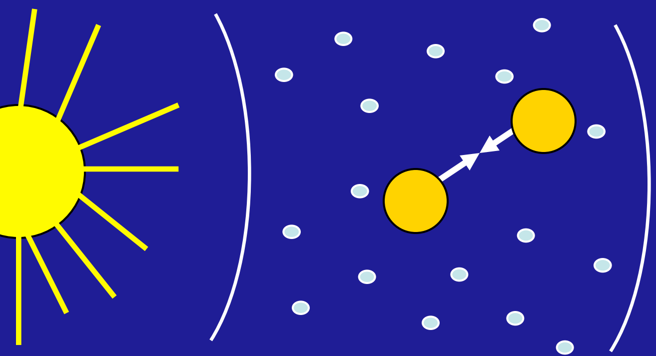


$$M_{iso} \approx 2\pi a(\Delta a_{zone})\Sigma \sim M_{Neptune}$$ @ 20-30 AU

$$M_{iso} \approx 2\pi a(\Delta a_{zone})\Sigma \sim M_{Mars}$$ @ 1.5 AU



Last Stages of Terrestrial Planet Formation

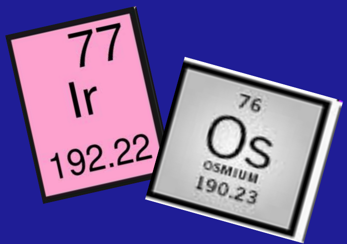


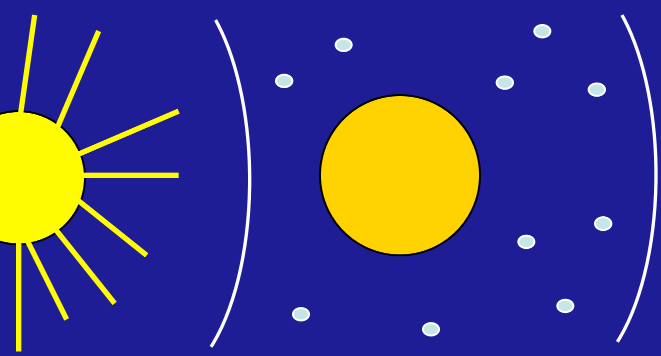
Giant Impacts:

Protoplanets' velocity dispersion increases

→ Giant Impacts

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

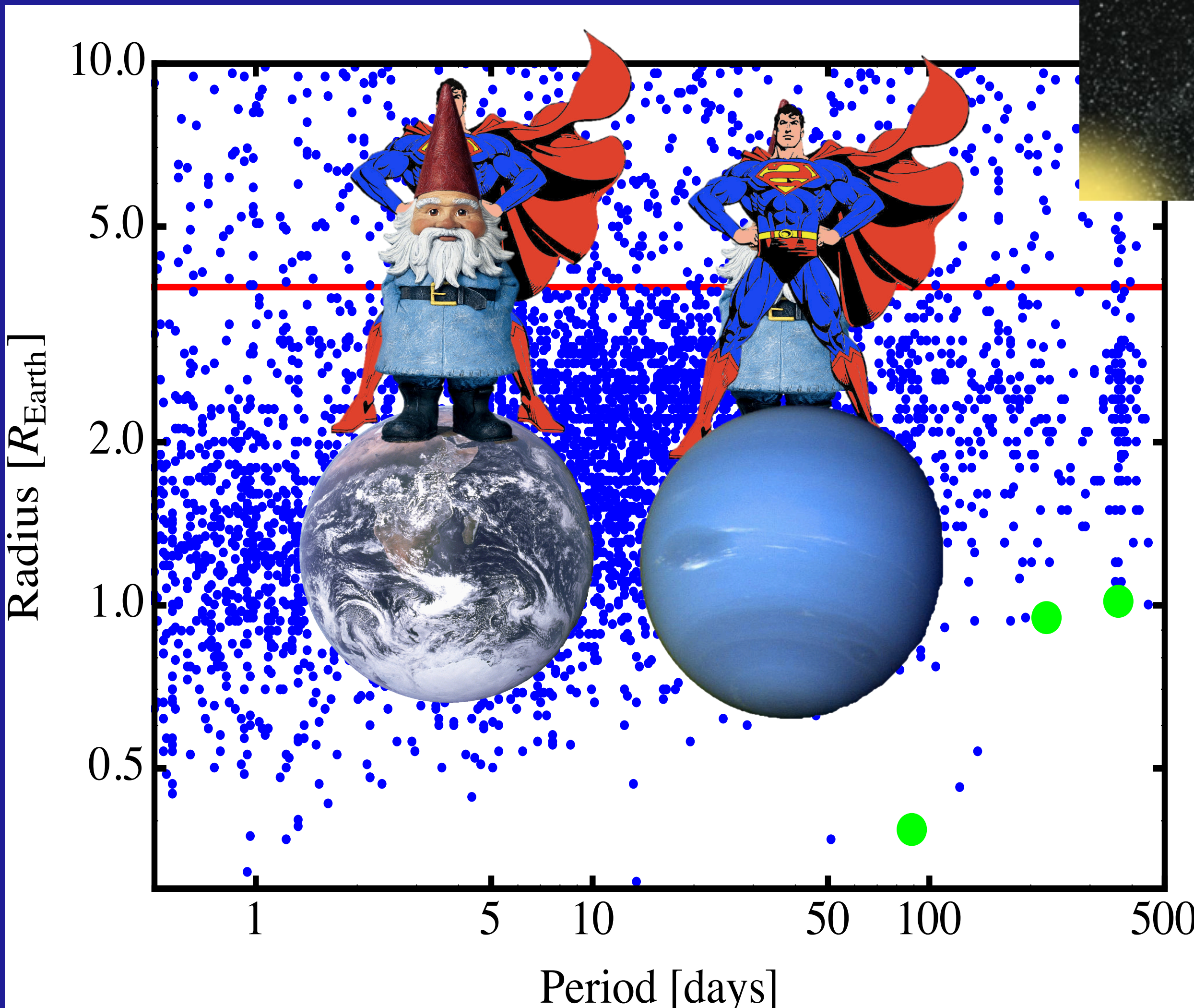


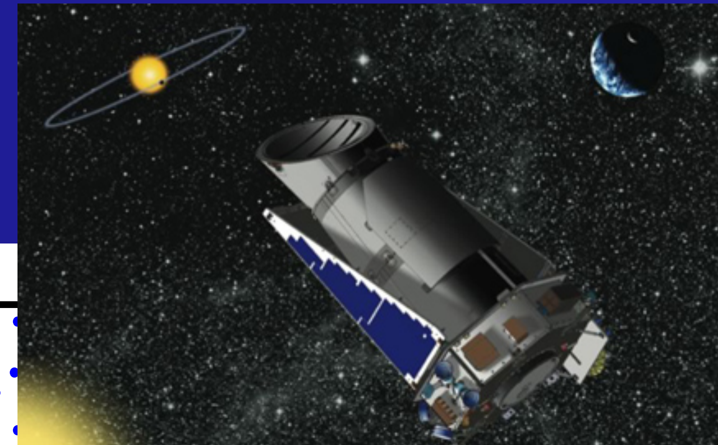


Clean up:

- Orbits planar & circular (e.g. Schlichting et al. 2012)
- Accretion & ejection of remaining planetesimals

Kepler Planets





4175 Planetary Candidates

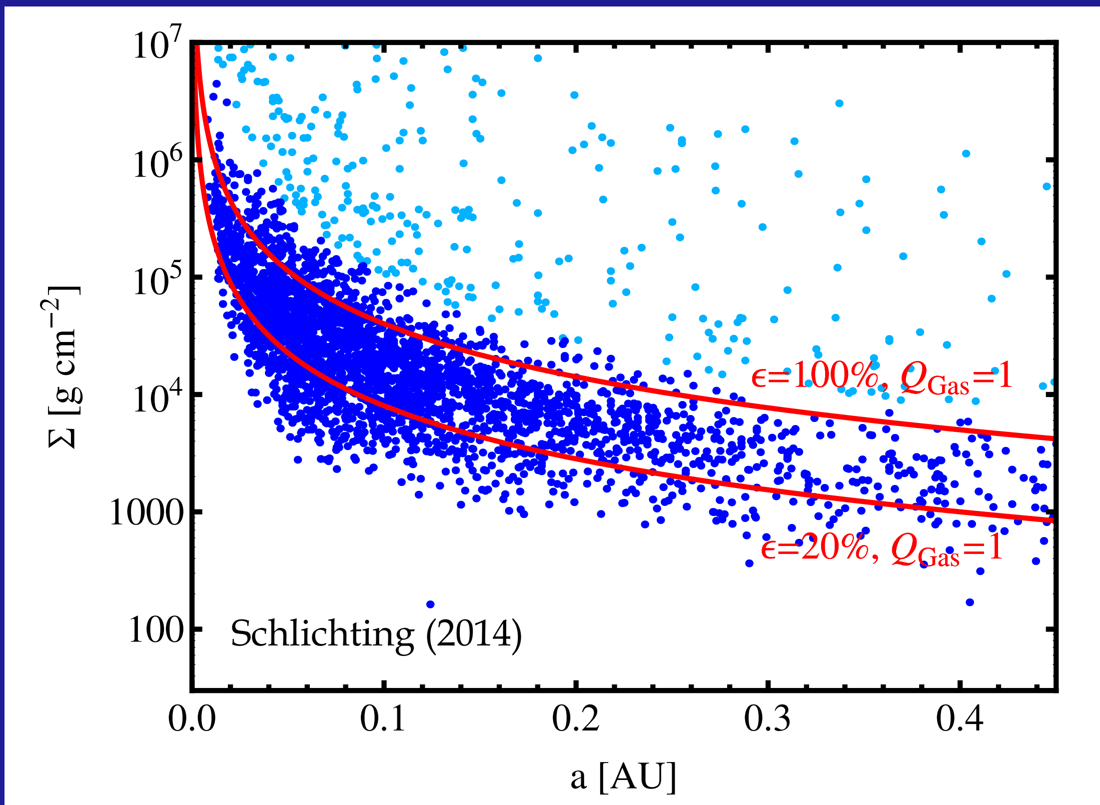
1218 Planets in Multi-Planet Systems

All planetary candidates discovered by Kepler as of Dec. 5th 2014.

Part I

Materials & Supplies

Forming Close-In Planets as Isolation masses



R > 5 R_{Earth}

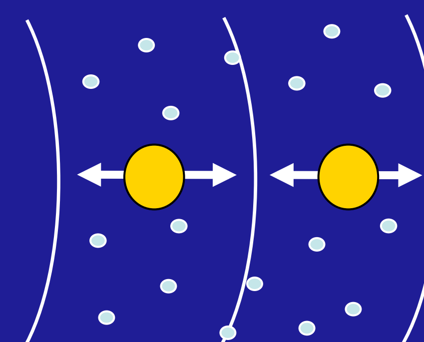
R < 5 R_{Earth}

$$Q_{Gas} \equiv \frac{c_s \Omega}{\pi G \Sigma_{gas}}$$

(Toomre 1964)

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

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

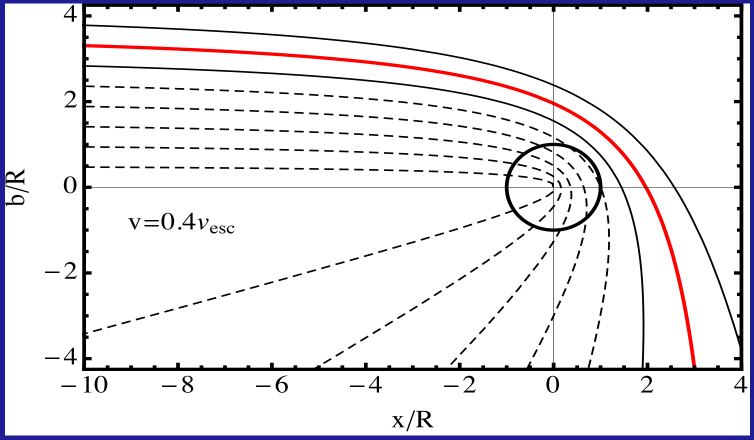


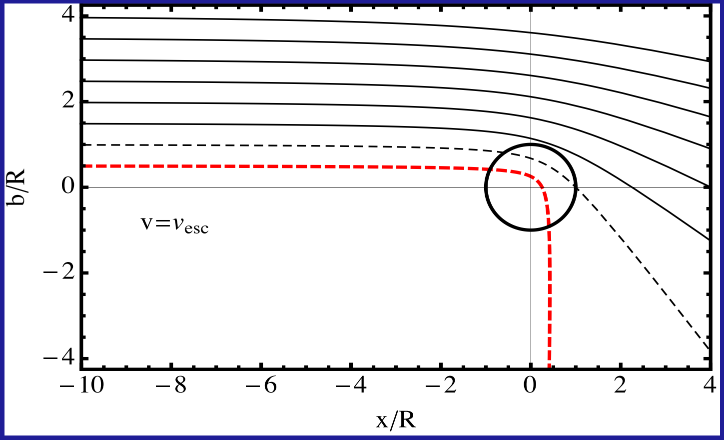
Viscous Stirring

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} $\sigma_{stirr} << \sigma_{coll}$





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

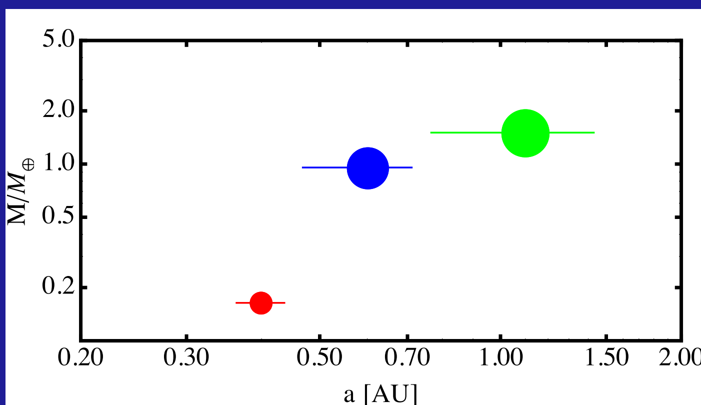
$$\sigma_{coll} \sim \pi R^2 \left(1 + \left(\frac{v}{v_{esc}}\right)^{-2}\right)$$

Example: Terrestrial Planets

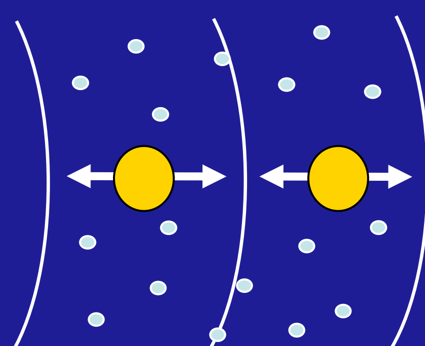
$$M_{GI} \simeq \frac{\left[2^{5/2}\pi a^2 \Sigma (\rho/\rho_\odot)^{1/6} (a/R_\odot)^{1/2}\right]^{3/2}}{M_\odot^{1/2}}.$$

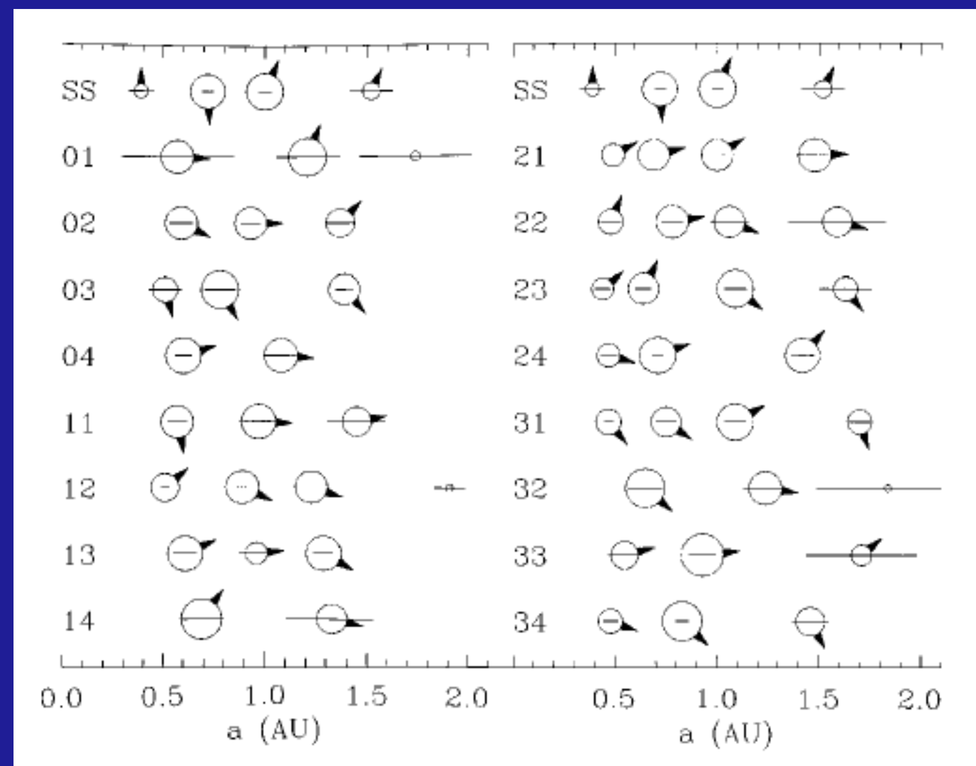
$M_{planet} \longleftrightarrow \Sigma$

Schlichting 2014



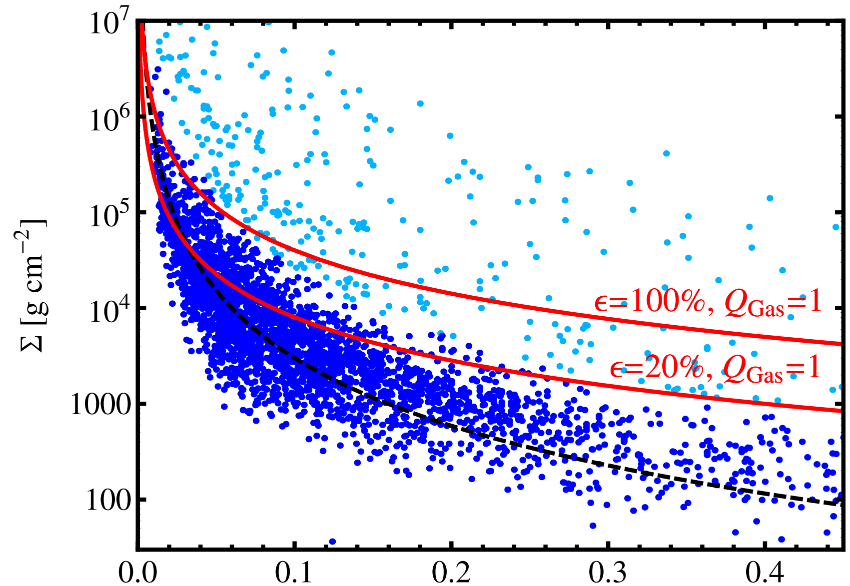
$$\Delta a \sim 2v_{esc} / \Omega$$



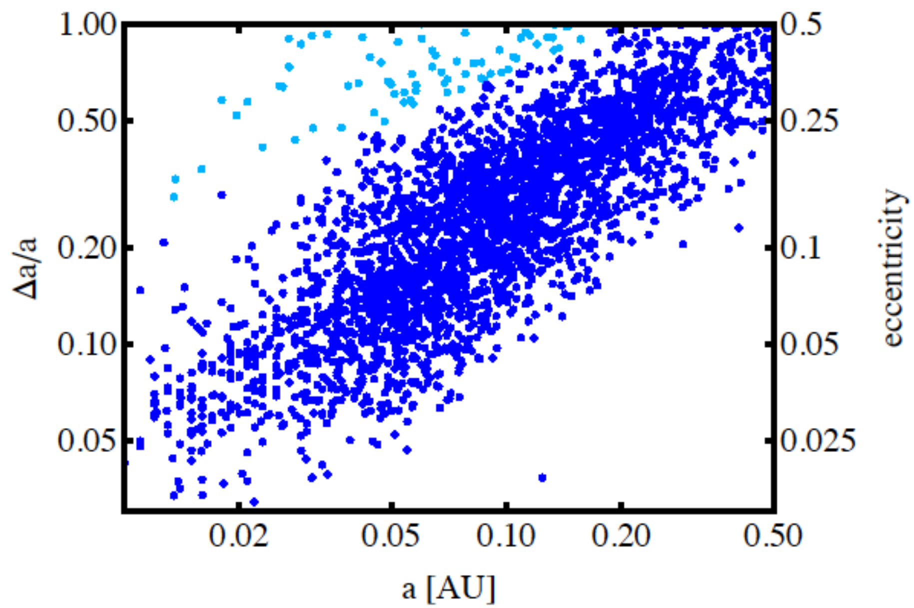


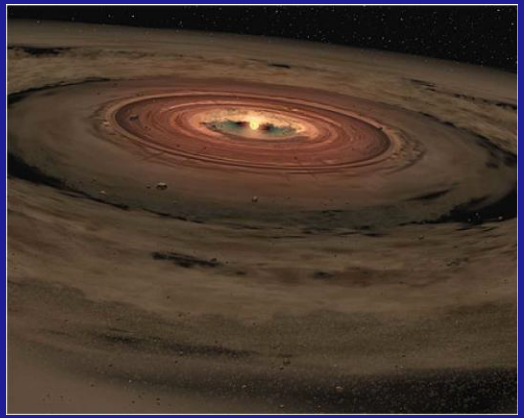
Chambers 2001

Forming Close-In Planet with Giant Impacts

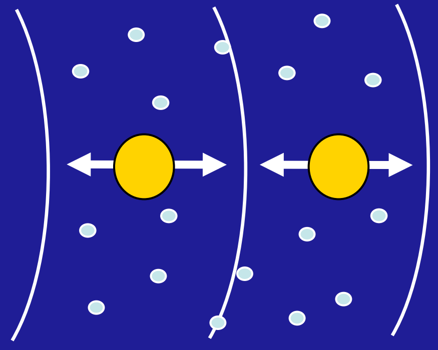


Schlichting (2014)

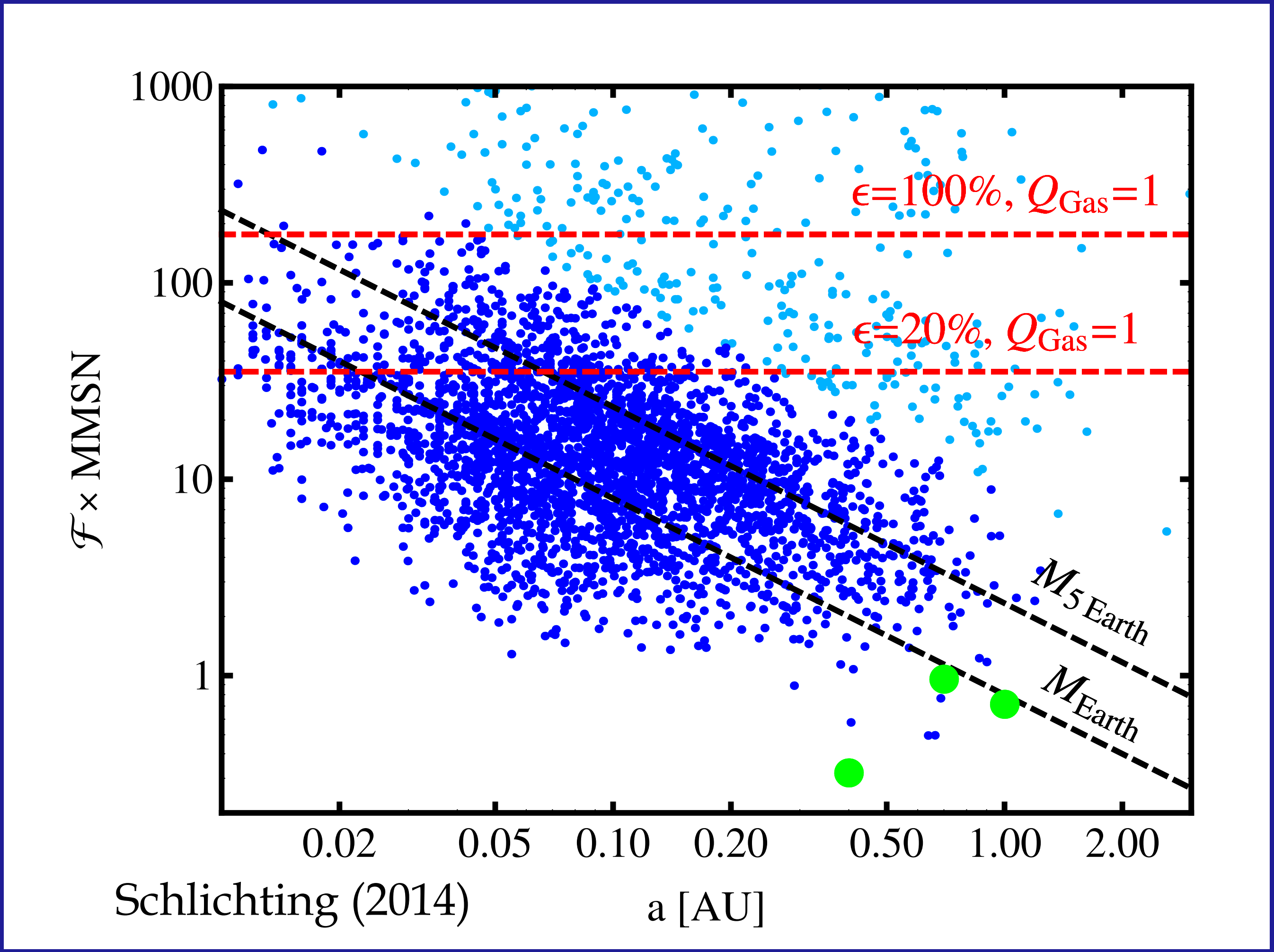


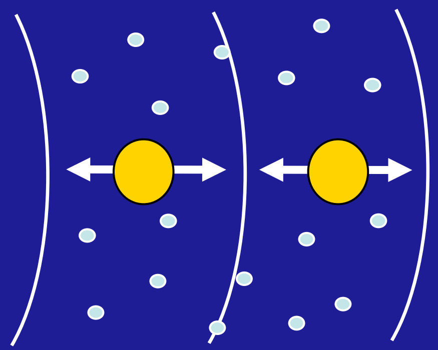


$$\Delta a \sim 2v_{esc} / \Omega$$



Minimum Disk Masses Required





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

Take Home Points I

Radial drift and/or migration must have played a key role in the origin of close-in Super-Earths and Mini-Neptunes

- Disk Stability (Schlichting 2014)
- Global Disk Masses
- Disk radial profiles (Raymond et el. 2014)
- Giant planet occurrence (Schlaufman 2014)

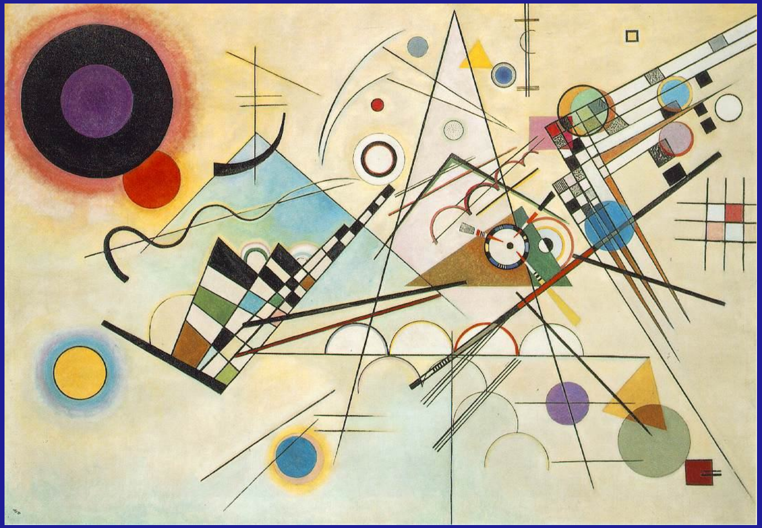
Formation of close in planets with Giant Impacts is a possibility, need massive inner disks, typically few tens MMSN (Raymond 2008, Hansen & Murray 2012).

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

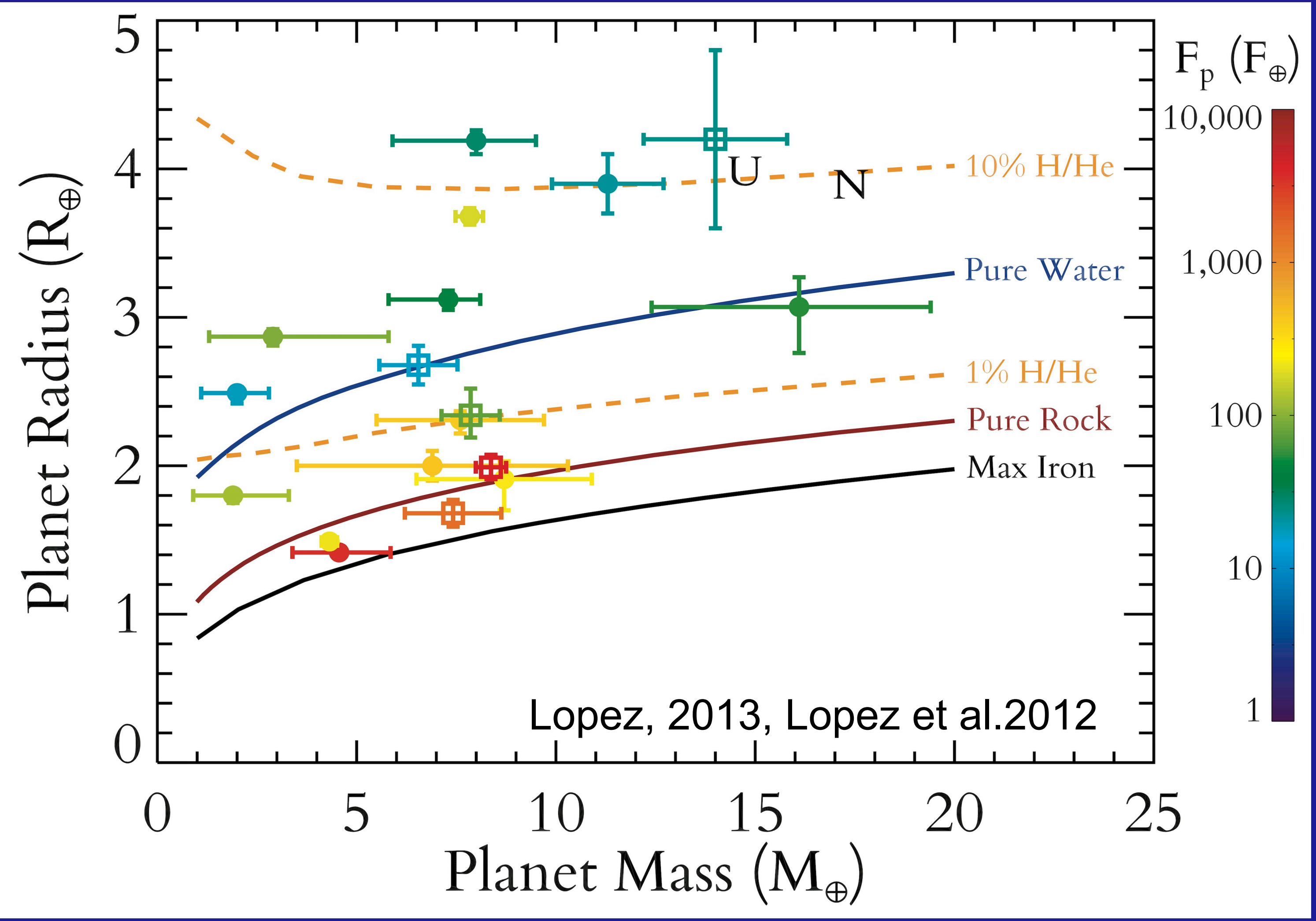
Need to examine planet formation with radial drift and/or migration
Growth times maybe determined by rate of material delivery into the inner disk

Part II

Composition & Structure

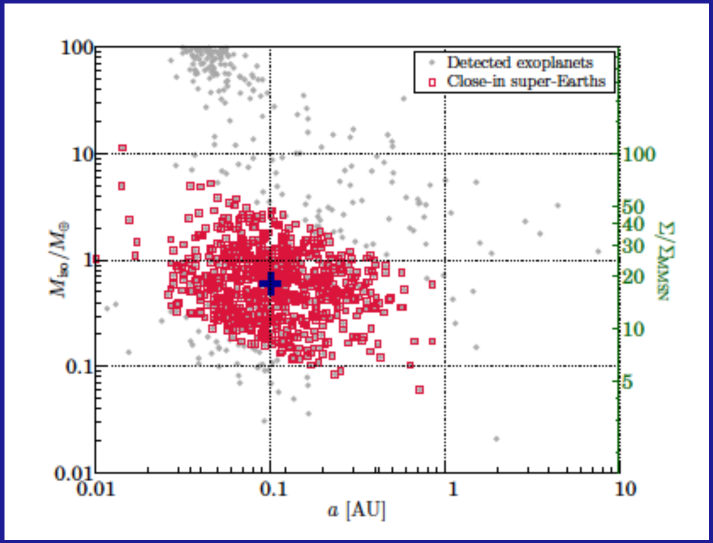


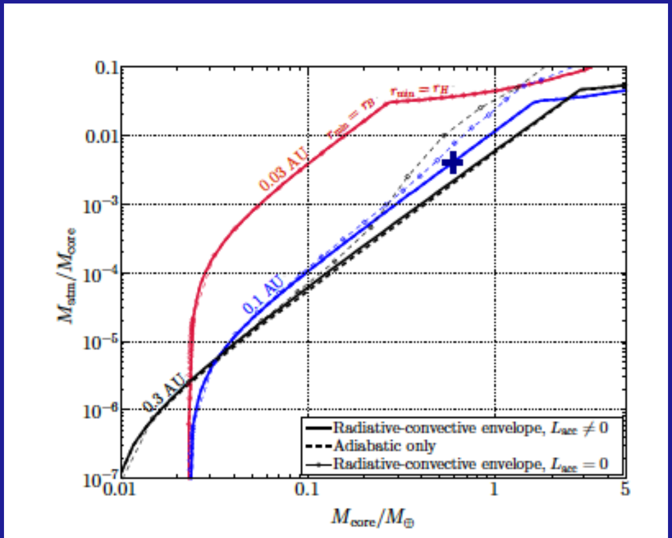
Exoplanet Atmospheres

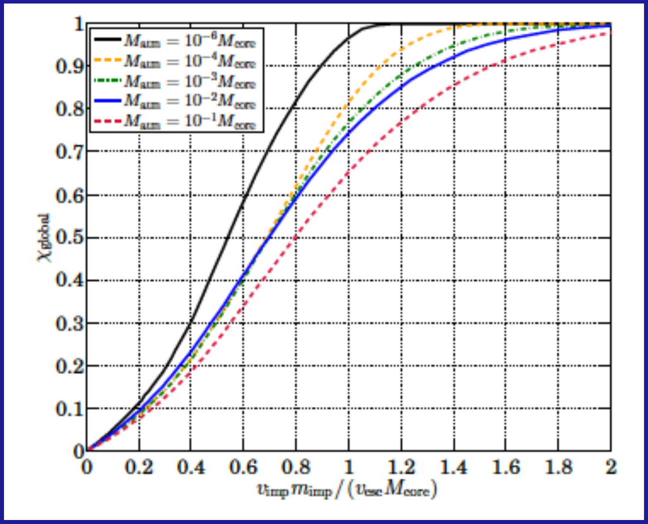


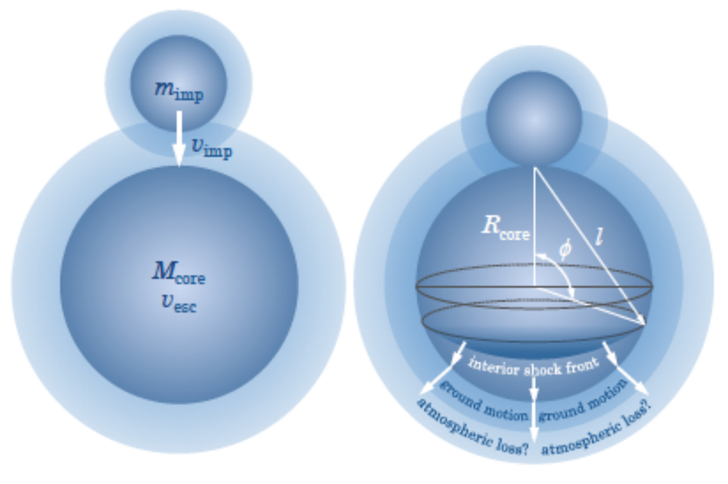
For comparison, the Earth's atmosphere contains less than 10^{-6} of its mass and has an atmospheric scale height that is only ~ 0.1% of its radius.

Formation of Close-In planets with Giant Impacts



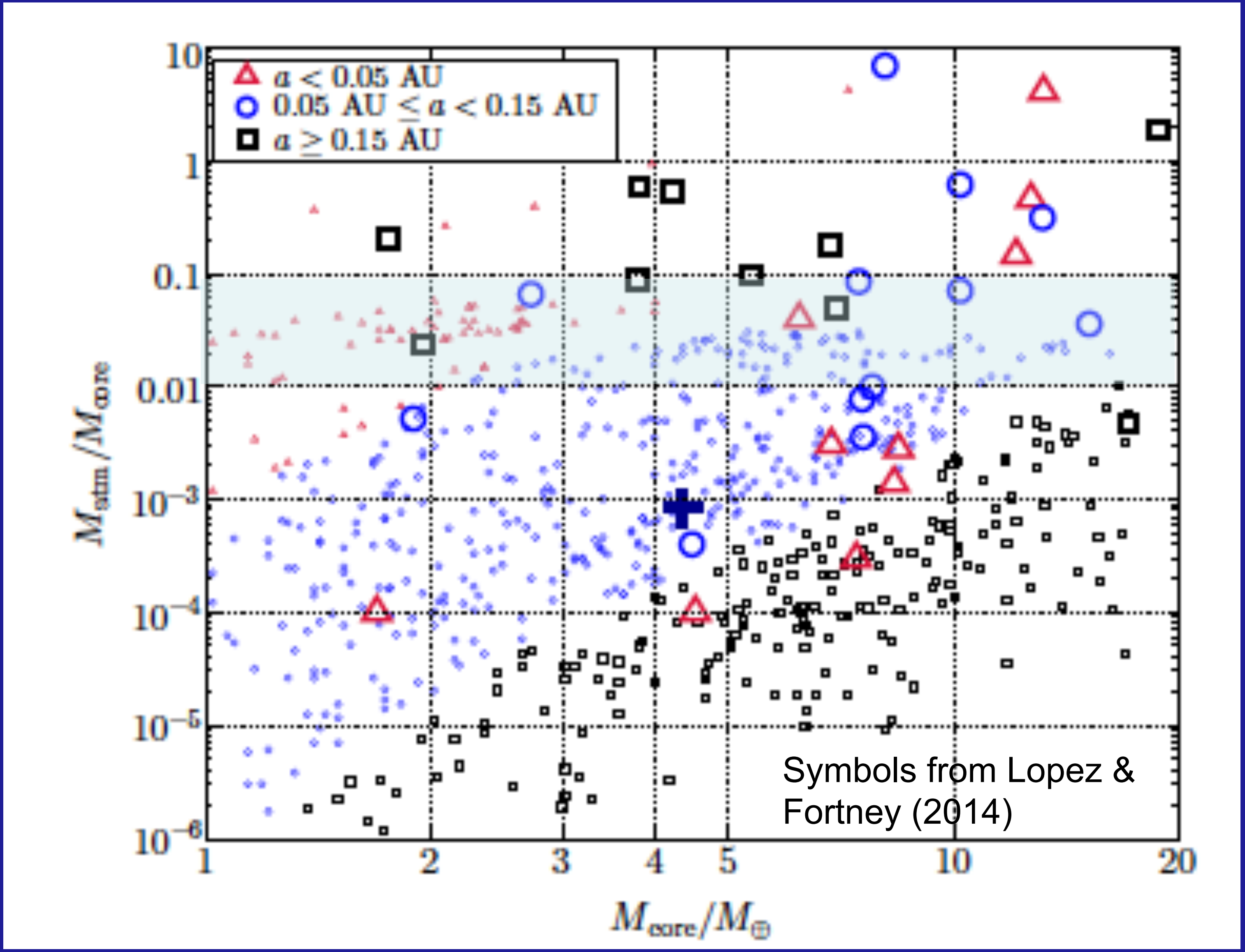






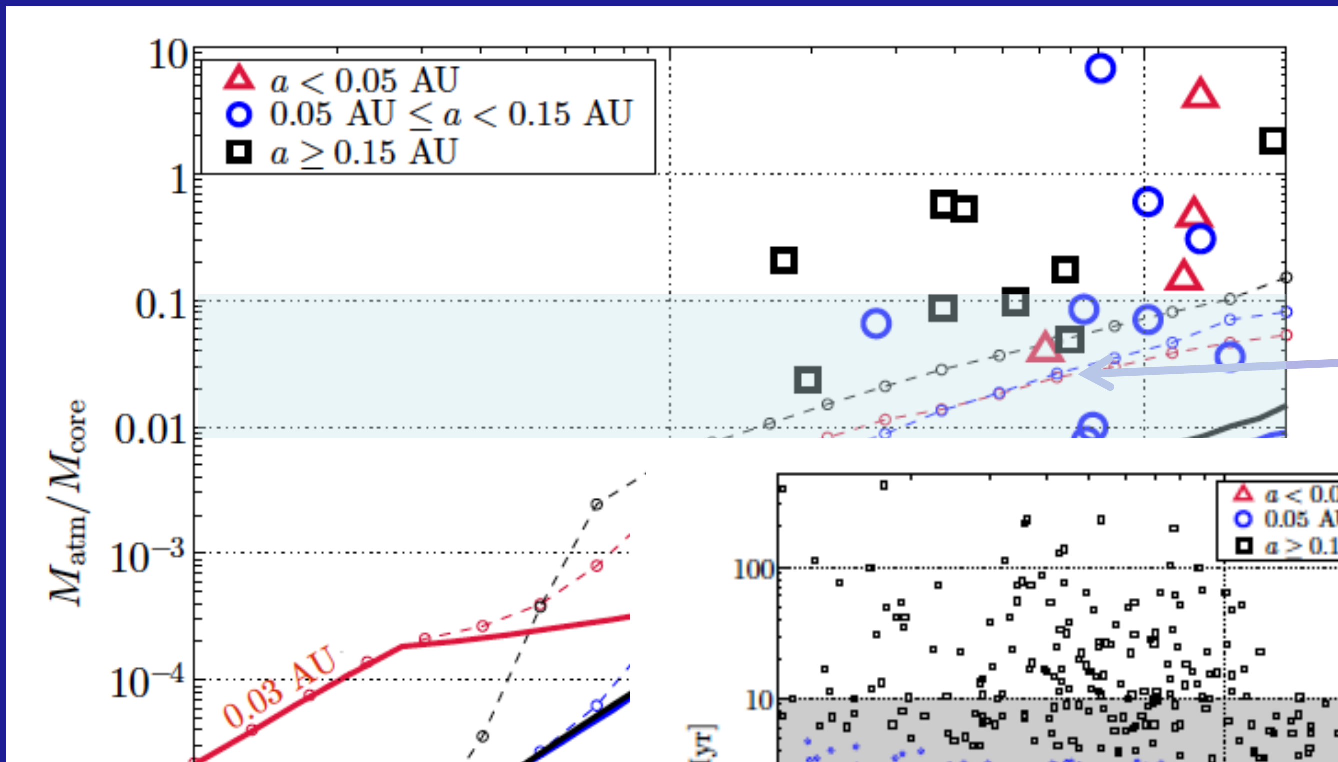
(Inamdar & Schlichting, 2015)

Formation of Close-In planets with Giant Impacts



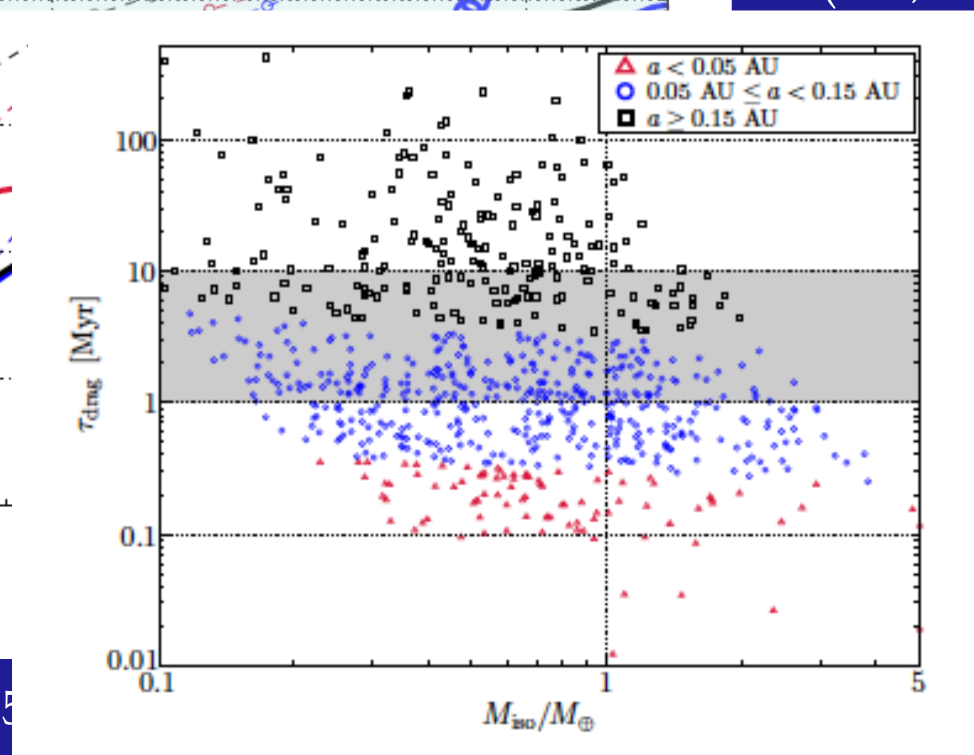
(Inamdar & Schlichting, 2015)

Envelope Accretion After Giant Impacts



Symbols from Lopez & Fortney (2014)

L_{acc}=0
(Lee, Chiang &
2014)



(Inamdar & Schlichting, 2015

Take Home Points II

Atmospheric masses of Isolation masses are small (10^{-3}) and atmospheric mass loss due to Giant Impacts significant leading to typical atmospheric masses of ~ 0.1%

→ Formation of 'mostly' rocky planets no problem

Atmospheric Accretion from partially depleted gas disk after Giant Impacts can explain atmospheres of up to a few % and less if:

1) $L_{acc} \sim 0$
2) Have massive inner disks, typically few tens MMSN
3) $\Sigma_{gas} / \Sigma_{dust} < 10$ to prevent radial drift.

It seems challenging to explain atmospheric masses >> several % with accretion from partially depleted gas disk after Giant Impacts.