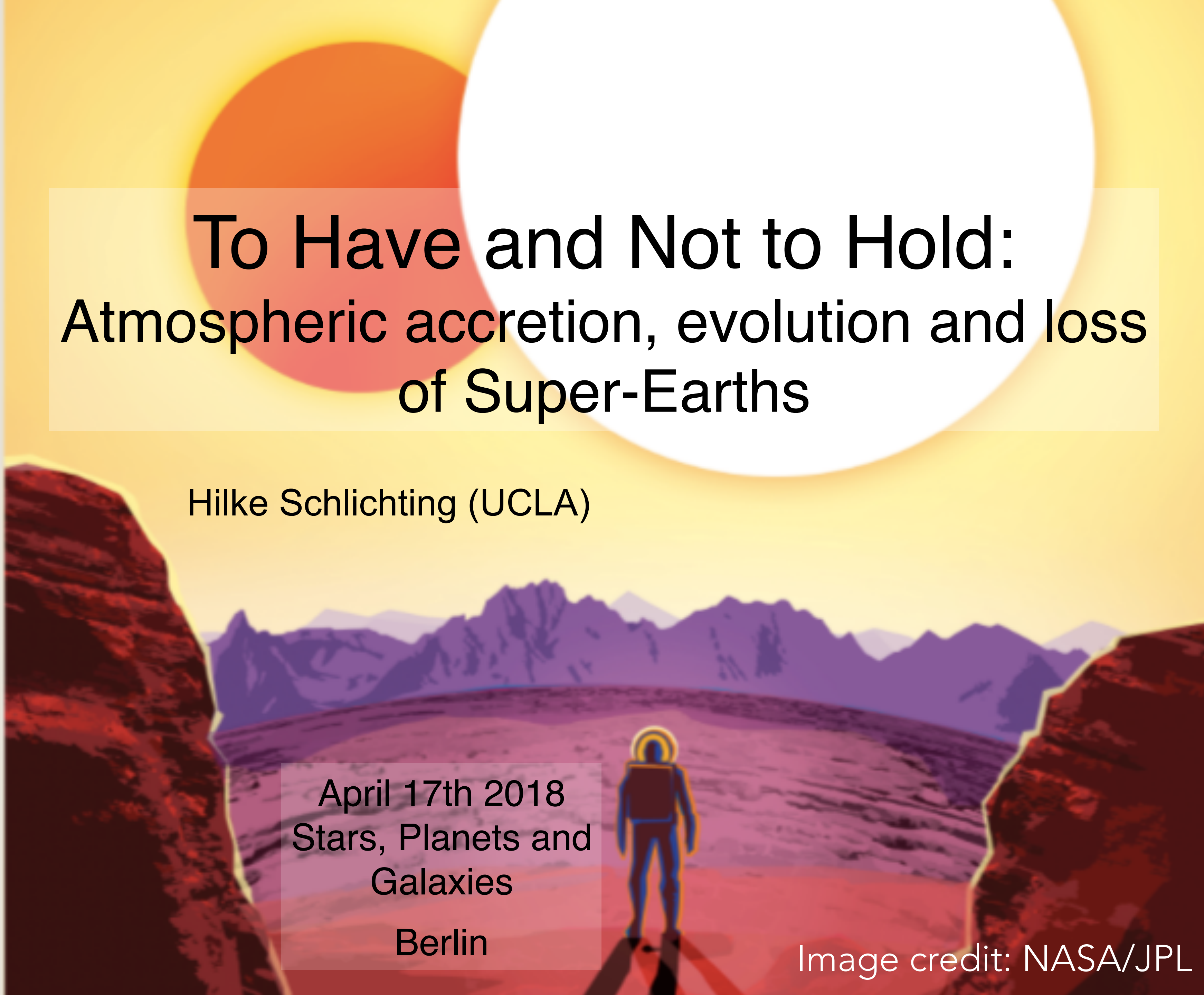


To Have and Not to Hold:

Atmospheric accretion, evolution and loss of Super-Earths

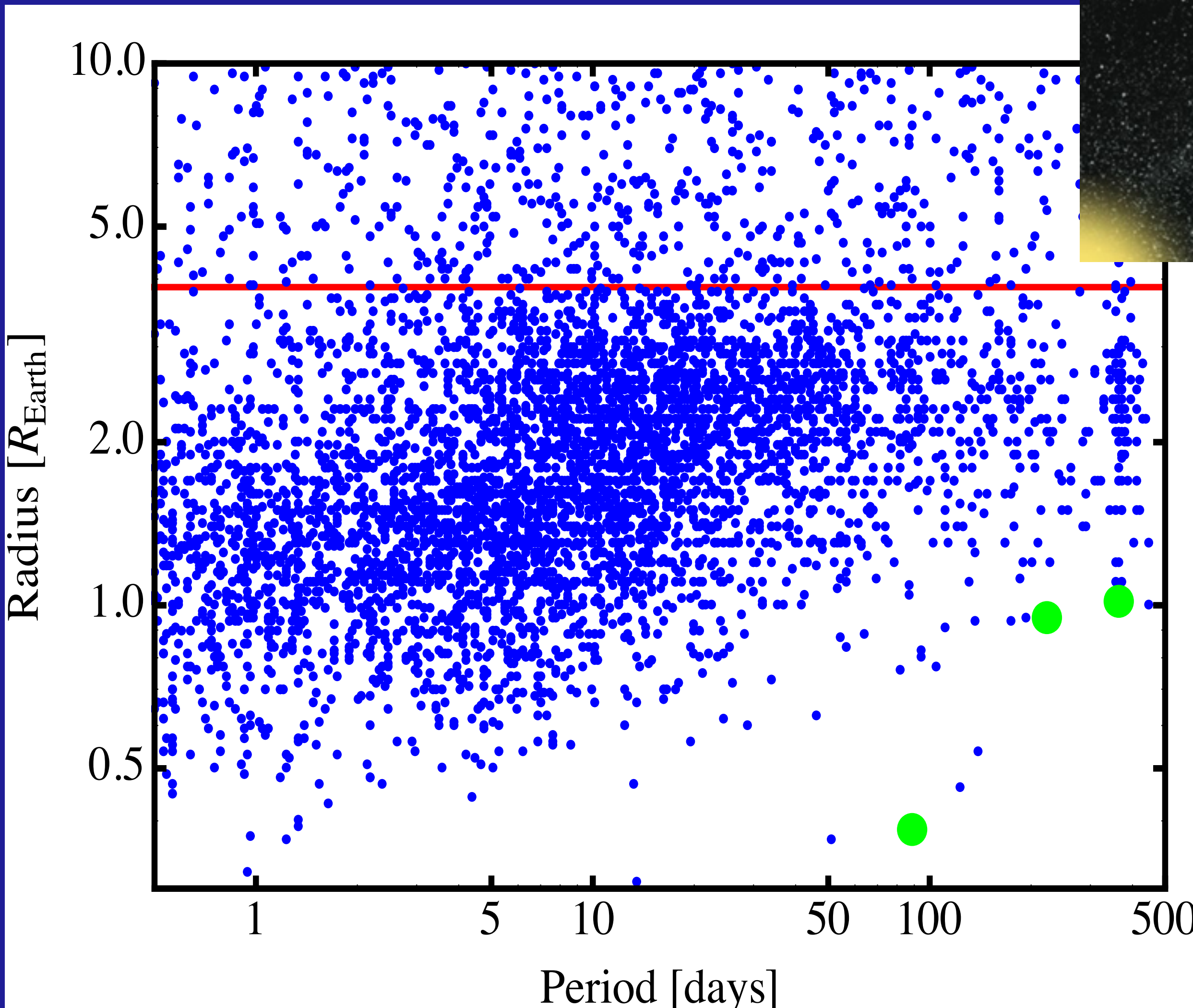
Hilke Schlichting (UCLA)

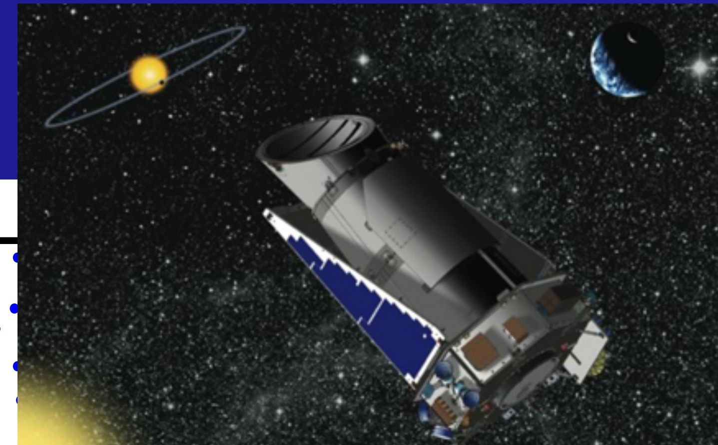
April 17th 2018
Stars, Planets and Galaxies

Berlin

Image credit: NASA/JPL

Kepler Planets



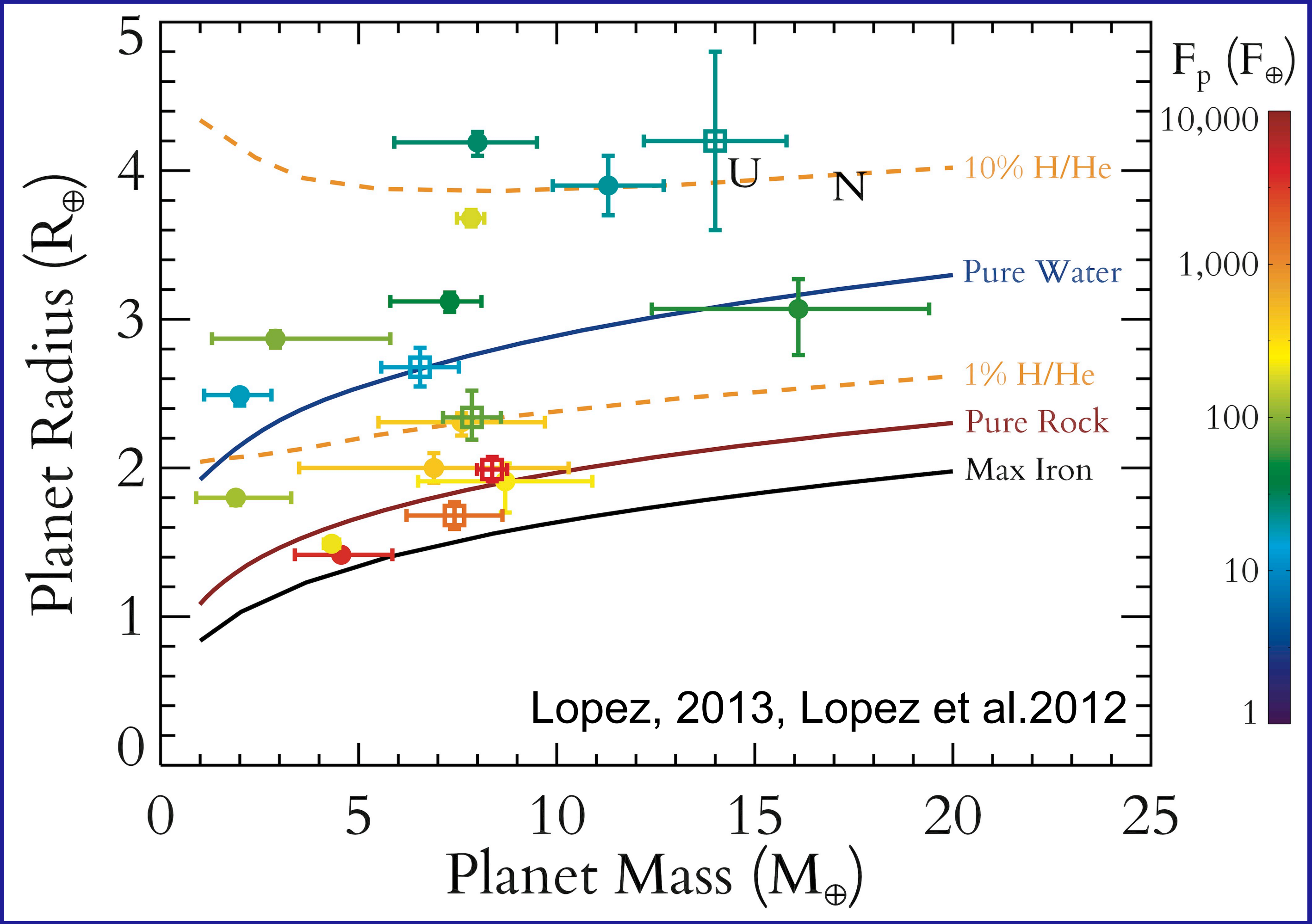


4175 Planetary Candidates

1218 Planets in Multi-Planet Systems

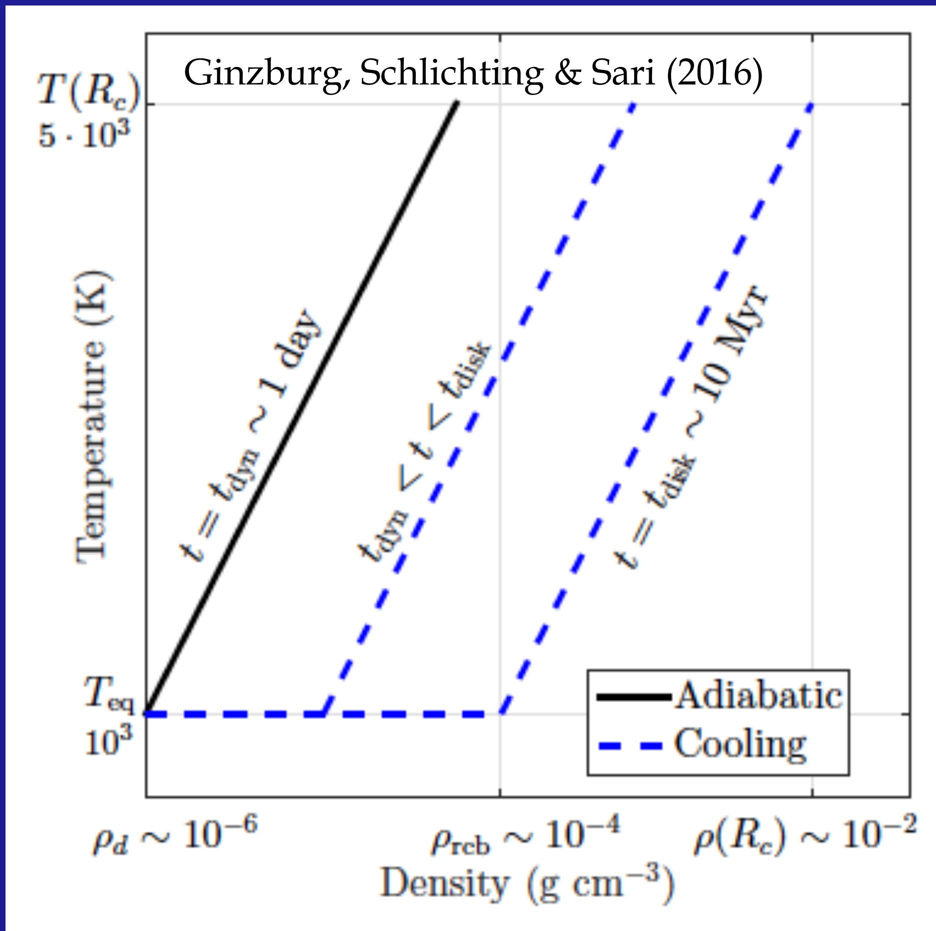
Most abundant Planets in Galaxy know to date (Fressin et al. 2013, Petigura et al. 2013)

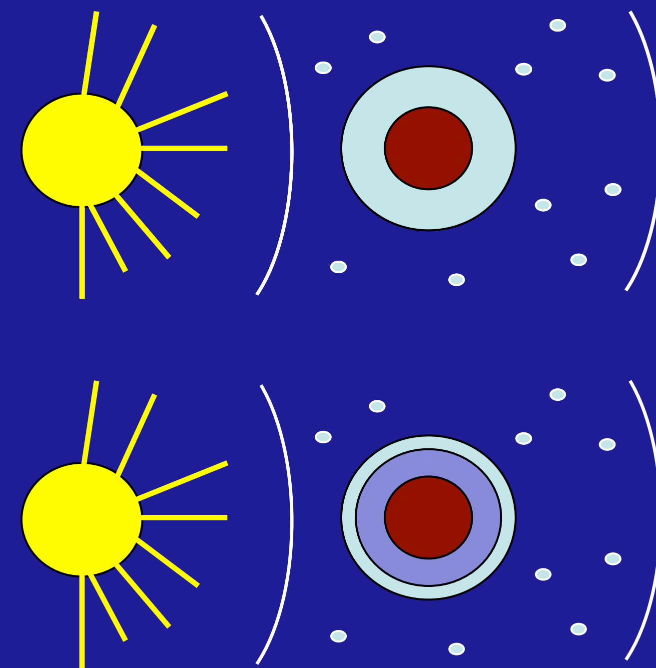
Exoplanet Atmospheres



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.

Envelope Accretion:





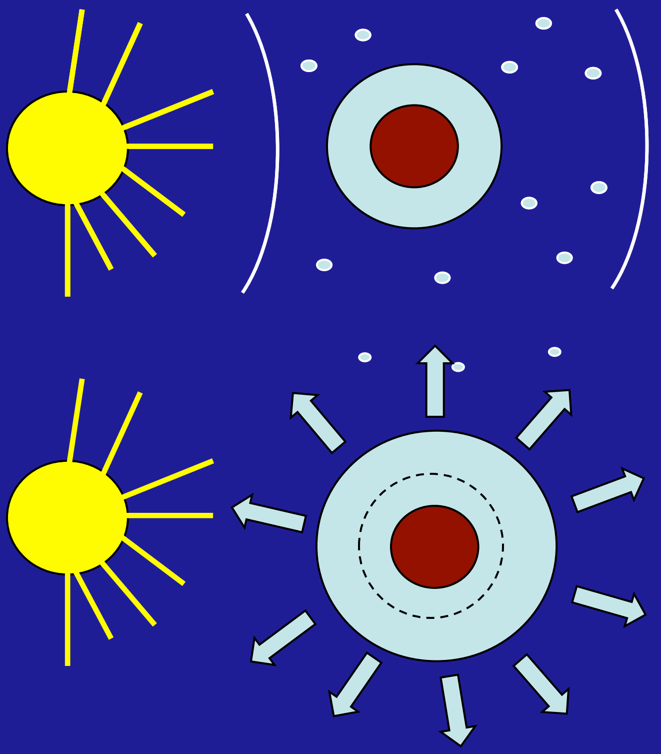
Accretion by cooling
(e.g. Inamdar & Schlichting (2015),
Lee & Chiang (2015))

$$f \approx 0.02 \left(\frac{M_c}{M_\oplus}\right)^{0.8} \left(\frac{T_{eq}}{10^3\ \mathrm{K}}\right)^{-0.25} \left(\frac{t_{disk}}{1\ \mathrm{Myr}}\right)^{0.5} \left(\frac{\kappa}{1 cm^2 g^{-1}}\right)^{-0.5}$$

f only depends logarithmically on ρ_{disk}

Spontaneous Evaporation due to Disk dispersal

$$\frac{E_{\rm evap}}{E_{\rm cool}} \sim \left(\frac{R_{\rm rcb}}{R_c}\right)^{-1/2}$$

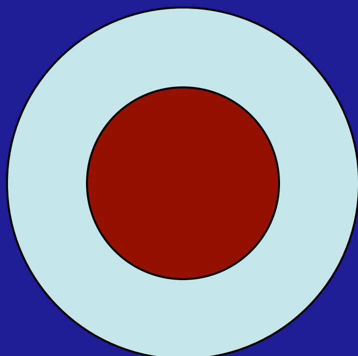


- Cooling of inner envelope can blow off the outer atmosphere
- Lose 25% (γ=1.2) to 70% (γ=7/5) of envelope mass
- R_{rcb} shrinks to $\sim R_c$ on $t \sim t_{disk}$
- sets initial condition for thermal evolution models

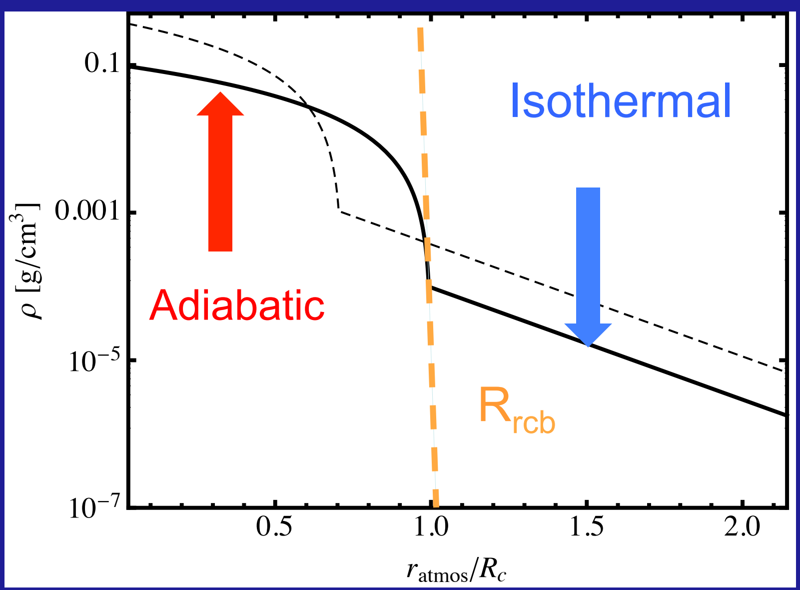
Ikoma & Hori 2012, Owen & Wu 2016, Ginzburg, Schlichting & Sari 2016

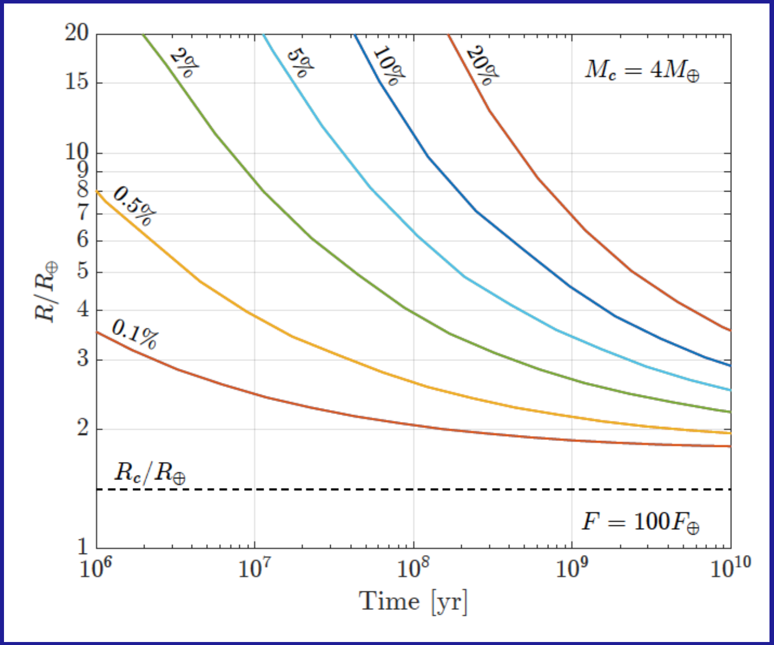
Two Cooling Regimes:

1) Energy Dominated by Envelope: Heavy envelopes



H/He Atmospheres containing more than 5% of total mass don't have enough energy to blow themselves away. Envelope cools and contracts over Gyrs.

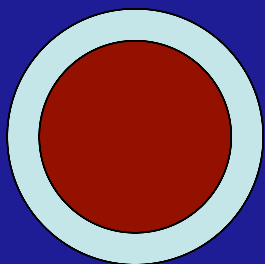




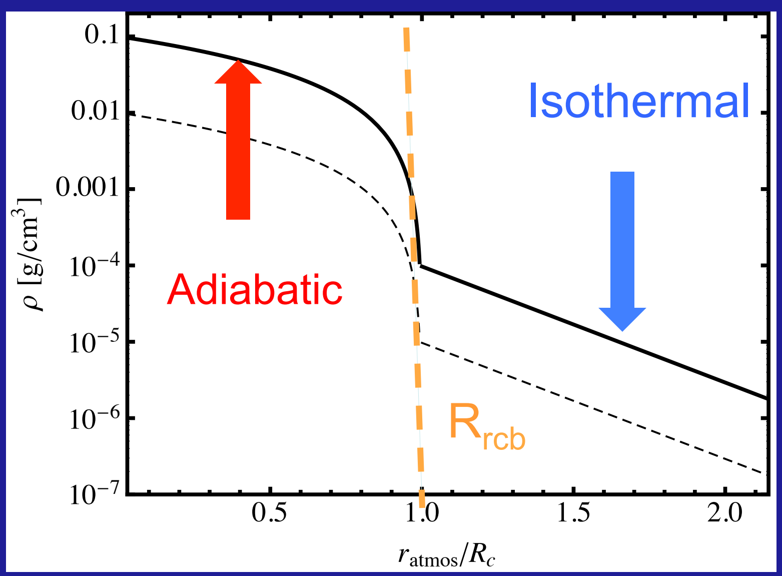
Inamdar & Schlichting 2016,
see also Rogers et al 2011, Lopez & Fortney 2013

Two Cooling Regimes:

2) Energy Dominated by Core:
Light Envelopes

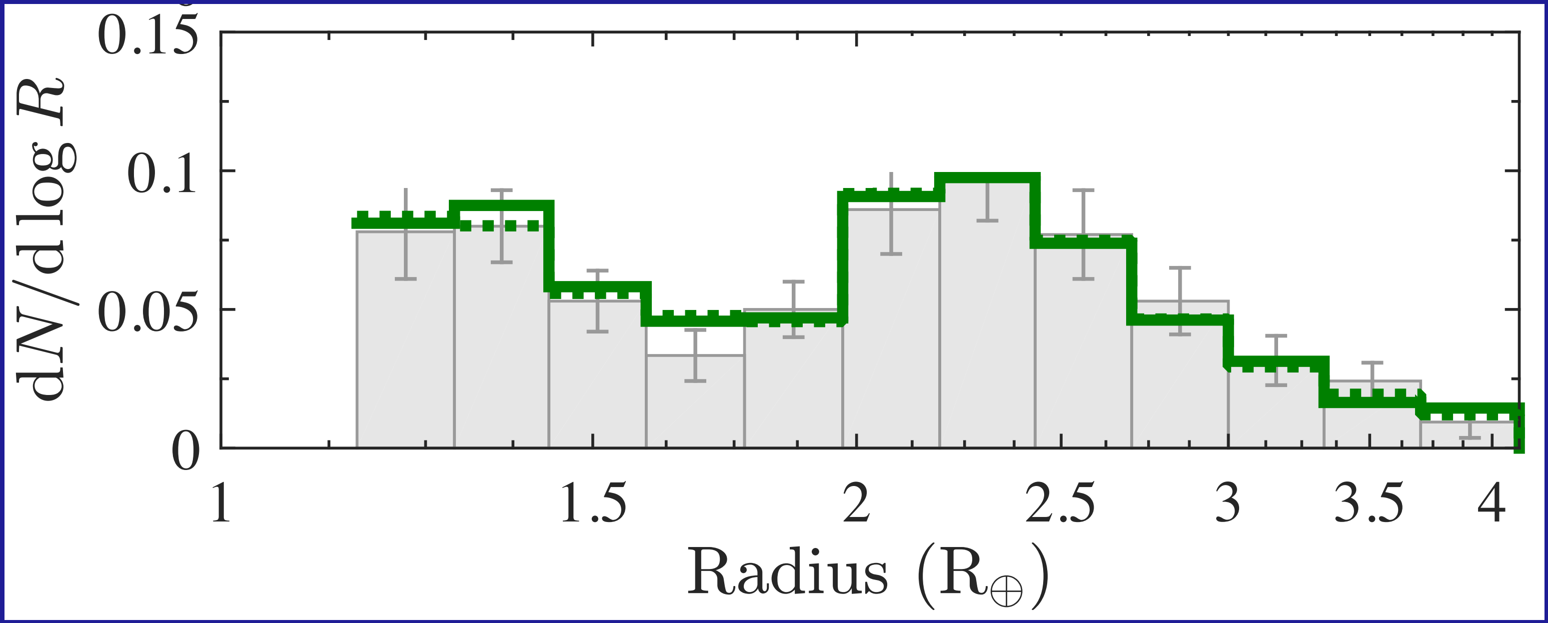


H/He Atmospheres containing less than 5% of total mass are lost completely, unless their loss timescales exceeds the age of the system or cooling timescale of the envelope.



Mass is lost at almost constant energy, R_{rcb} is constant and ρ_{rcb} decreases with time making subsequent loss even easier (energetically).

Comparison with Observations:



Ginzburg, Schlichting & Sari 2017

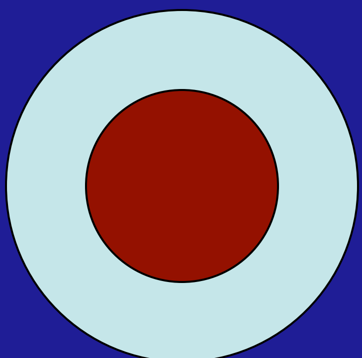
Can produce observed bimodal size distribution by accretion and core-powered mass loss alone (no need for photo-evaporation).

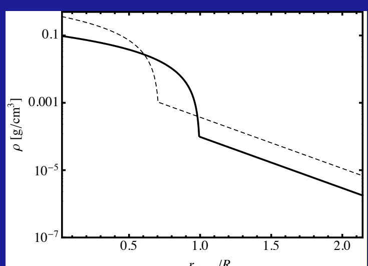
Mass distribution from Marcy et al. 2014 and radius data from Fulton et al. 2017

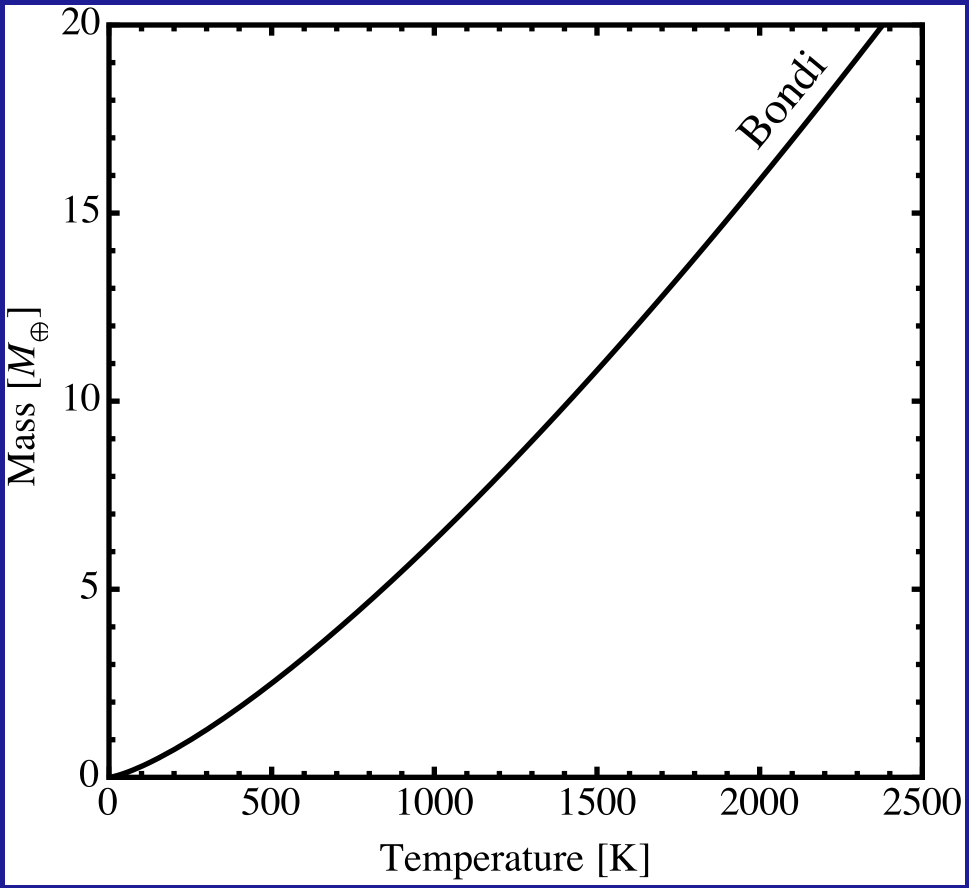
Atmospheric Mass loss due to Cooling:

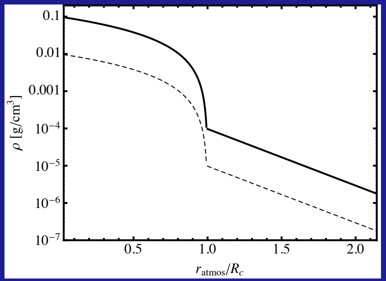
$$t \sim \frac{R'_B}{c_s} \left(\frac{R_{rcb}}{R'_B} \right)^{(3\gamma-4)/(\gamma-1)} \exp\left(\frac{R_B}{R_{rcb}} - 1 \right),$$

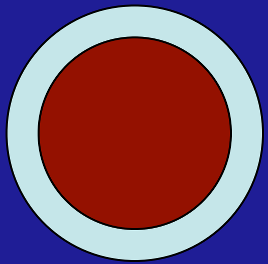
See also Owen & Wu 2016







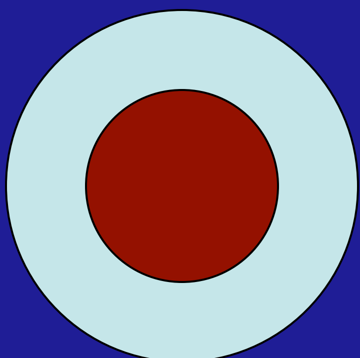


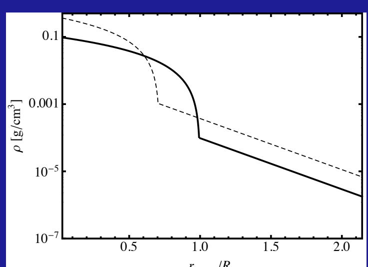


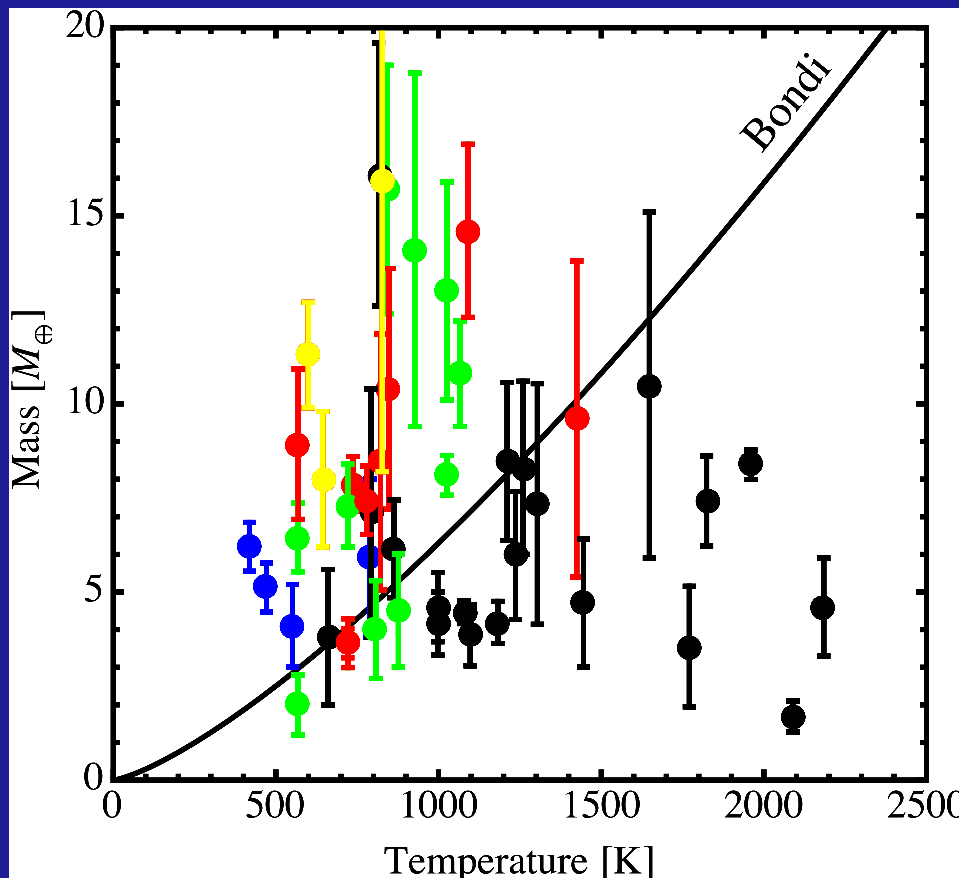
Atmospheric Mass loss due to Core Cooling:

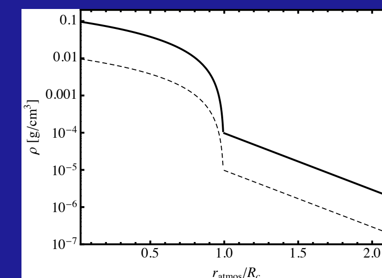
$$t \sim \frac{R'_{\mathrm{B}}}{c_s}\left(\frac{R_{\mathrm{rcb}}}{R'_{\mathrm{B}}}\right)^{(3\gamma-4)/(\gamma-1)} \exp\left(\frac{R_{\mathrm{B}}}{R_{\mathrm{rcb}}}-1\right),$$

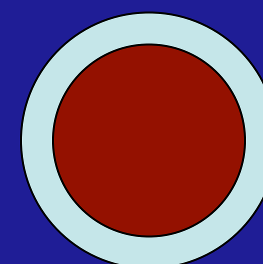
See also Owen & Wu 2016









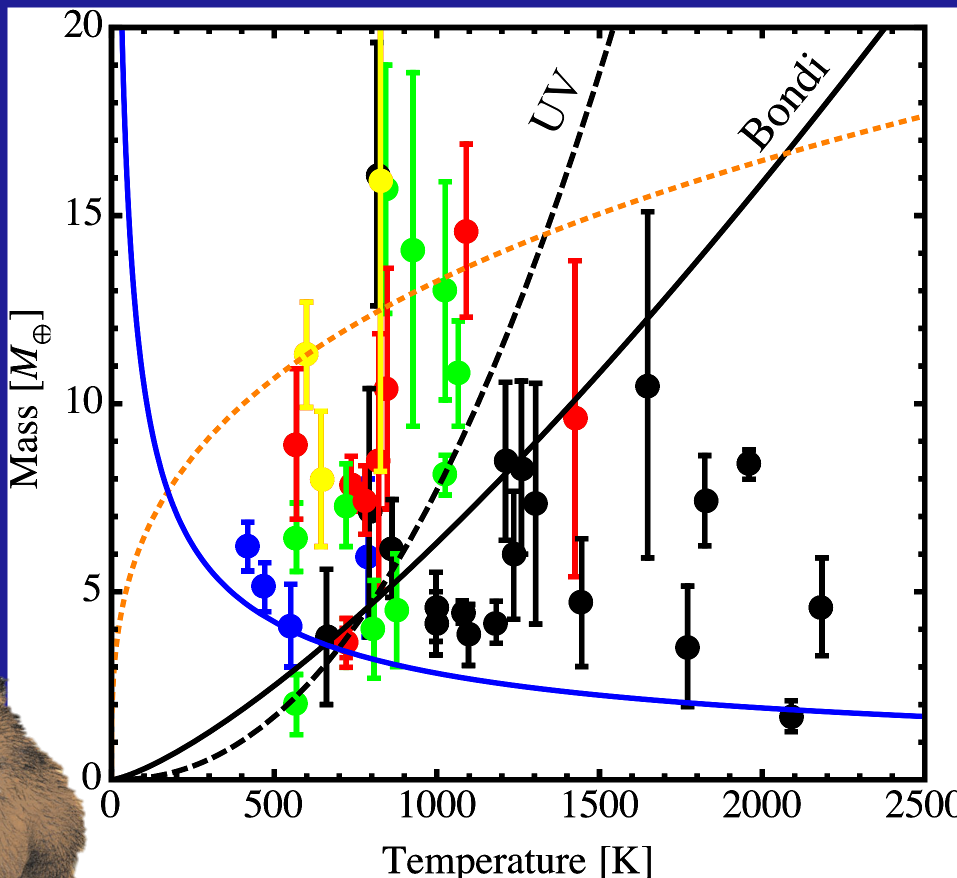


$M_{gas}/M_p < 0.3\%$
$0.3\% < M_{gas}/M_p < 1\%$
$1\% < M_{gas}/M_p < 5\%$
$5\% < M_{gas}/M_p < 10\%$
$10\% < M_{gas}/M_p$

Ginzburg, Schlichting & Sari (2016)
Schlichting (2018)

Goldilocks Regime

Ginzburg, Schlichting & Sari (2016)



$M_{gas}/M_p < 0.3\%$
$0.3\% < M_{gas}/M_p < 1\%$
$1\% < M_{gas}/M_p < 5\%$
$5\% < M_{gas}/M_p < 10\%$
$10\% < M_{gas}/M_p$

(UV losses: e.g. Murray-Clay et al. 2009, Lopez & Fortney 2013, Tu et al. 2015)

Take Home Points I

1) Planets shed their outer layers (dozens of percents in mass) following disk dispersal (even without photo-evaporation).

2) Atmospheres shrink in a few Myr to thickness comparable to the core radius.

3) Light atmospheres can be blown away by heat from the core.

4) Heavy atmospheres cool and contact on Gyr timescales.

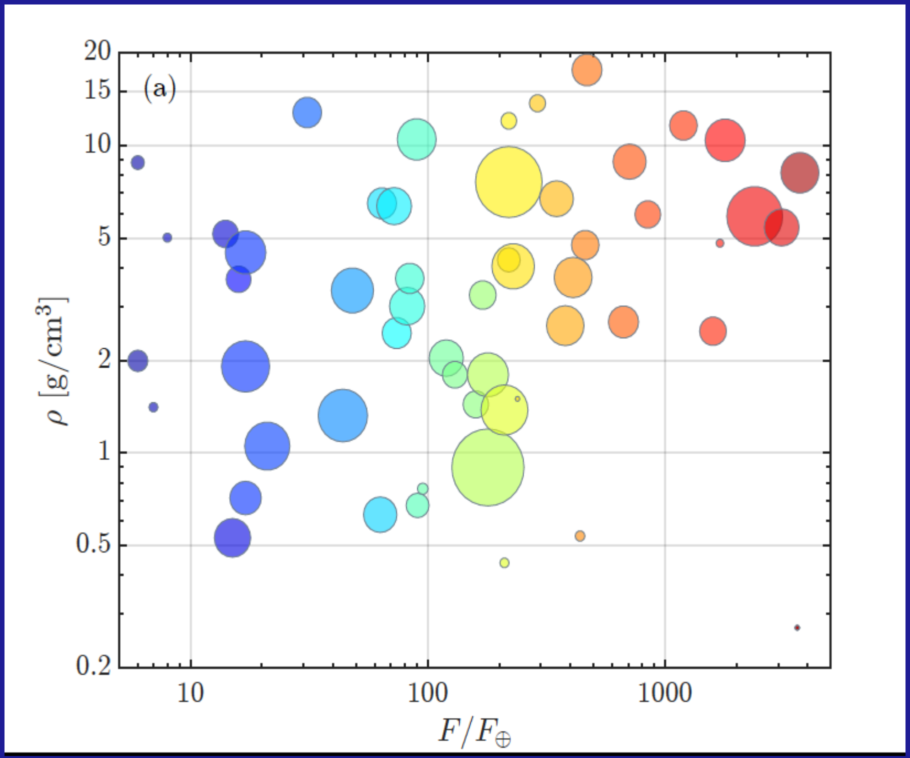
Part II

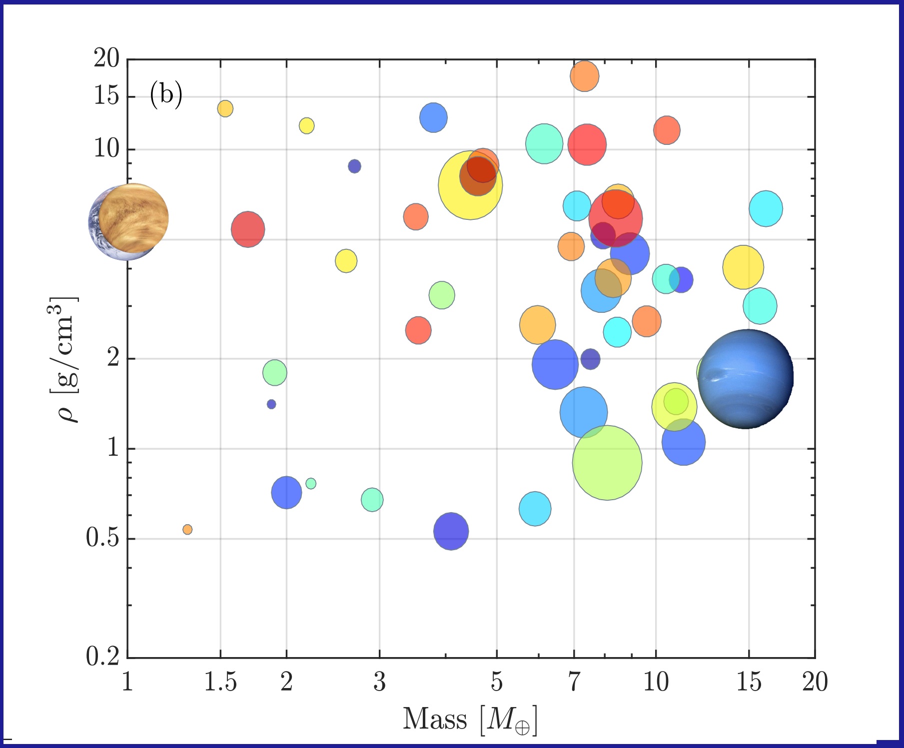
Why so Different?

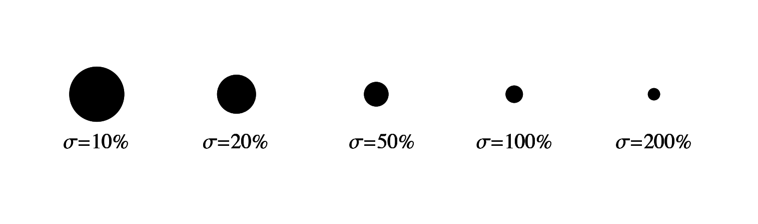





Exoplanet Densities



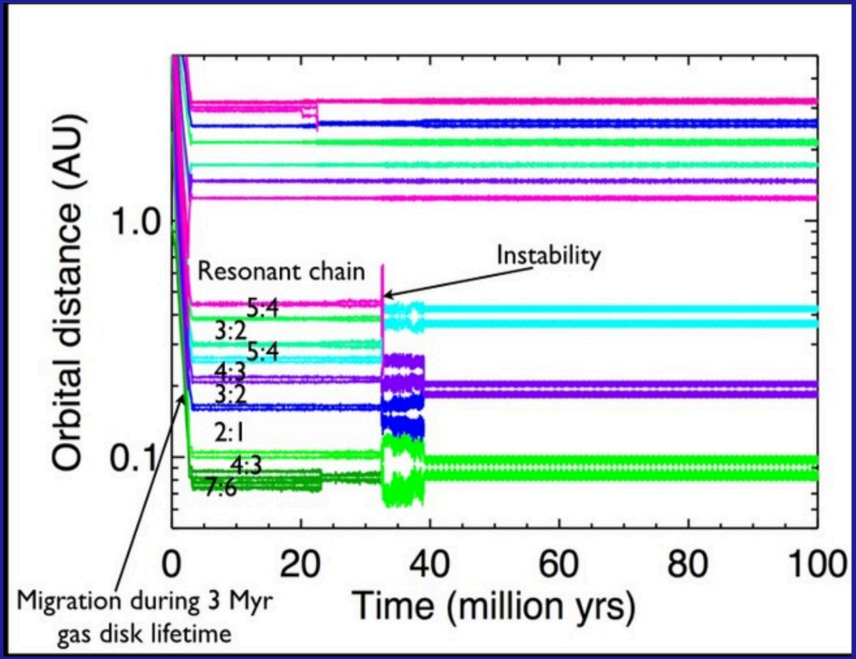




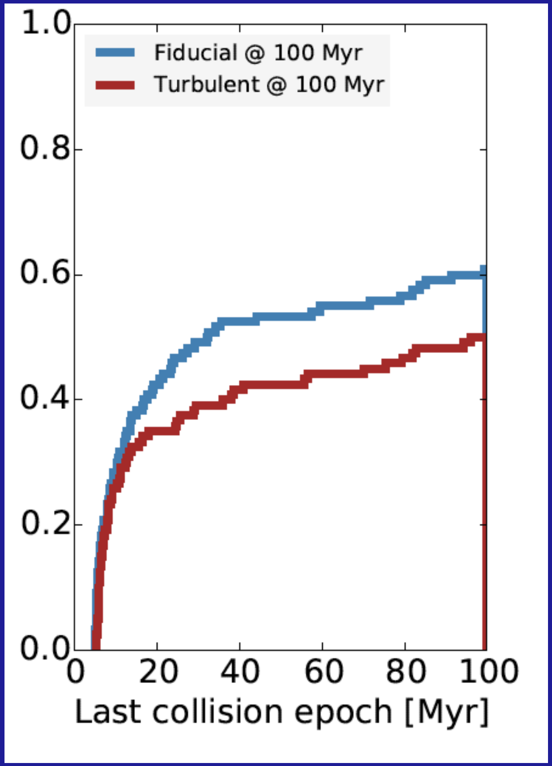
Inamdar & Schlichting 2016

Data from Weiss & Marcy 2014, Juntof-Hutter et al. 2015, Barros et al. 2015

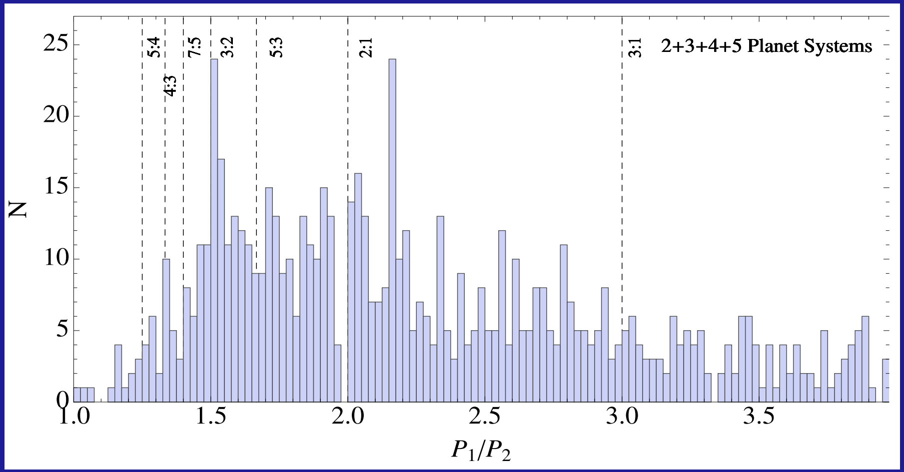
Late Collisions & Kepler Multiple Planet Systems



Cossou et al. 2014



Izidoro et al. 2017



4175 Planetary Candidates

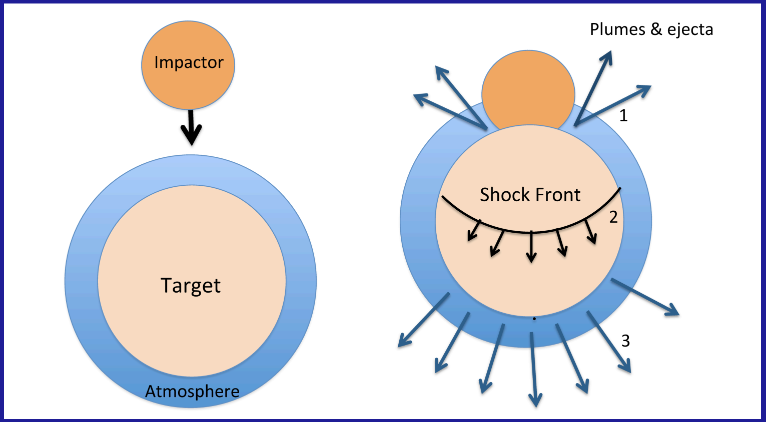
1218 Planets in Multi-Planet Systems

Lissauer et al. 2011, Fabrycky et al. 2014, Goldreich & Schlichting 2014

Giant Impacts & Atmospheric Mass Loss

1) High-velocity impactor hits the surface of the planet

2) Its velocity is sharply decelerated and its kinetic energy is rapidly converted into heat and pressure resulting in something analogous to an explosion (Zel'dovich & Raizer, 1967).



e.g. Genda & Abe 2003, 2005, Schlichting et al. 2015

Mechanical part

i) The impact launches a strong shock.

ii) The shock propagates through the planet causing a global ground motion.

iii) This ground motion launches a shock into the atmosphere, which can lead to significant atmospheric loss.

Thermal part

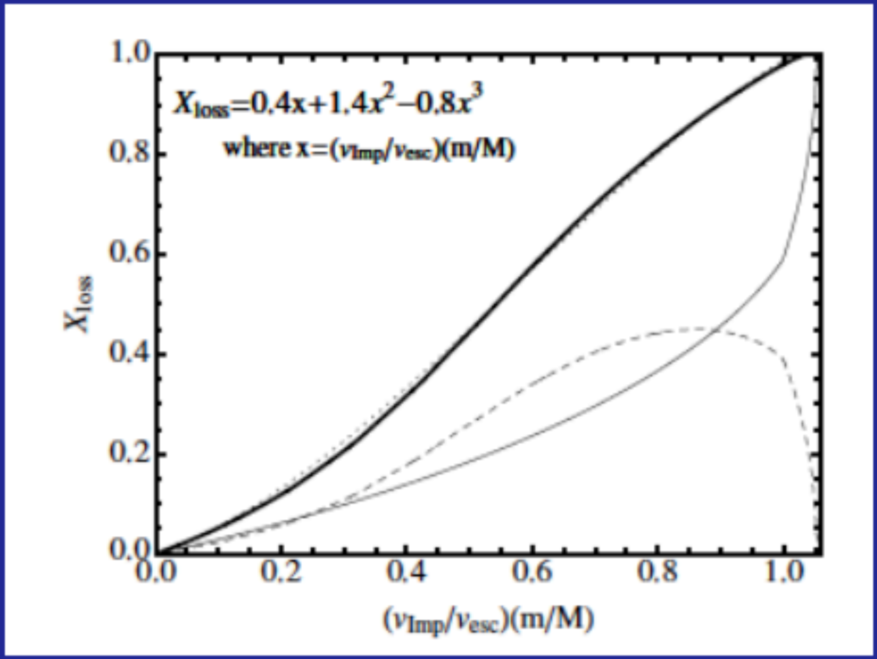
i) The impact heats the core.

ii) The core exchanges heat with the envelope.

iii) The envelope expands and will be partially or fully lost

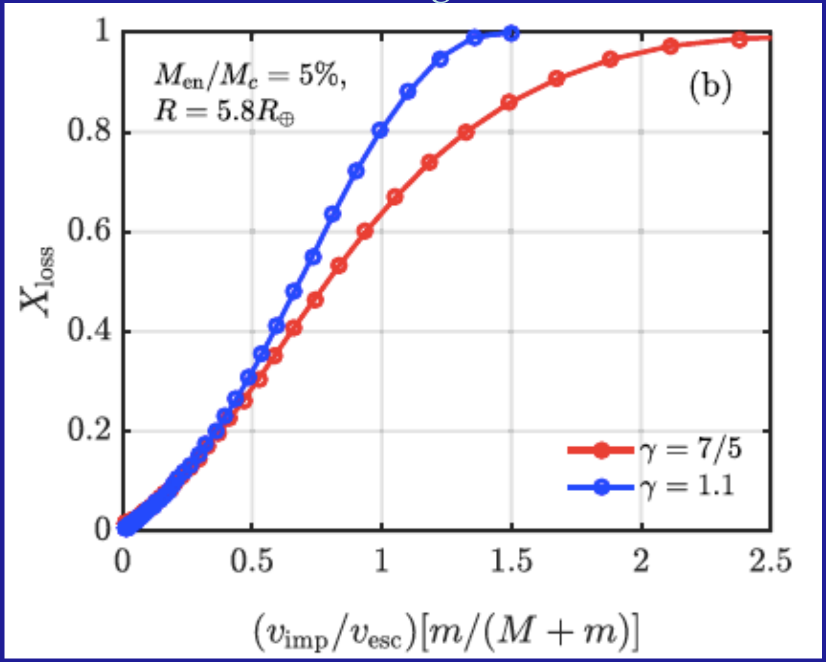
Giant Impacts: The 'Mechanical part'

Shock in plane-parallel isothermal/adiabatic atmosphere: Type II self-similar solutions (e.g. Raizer 1964; Grover & Hardy 1966)



Global atmospheric mass loss consists of two components (Schlichting et al. 2015)

Inamdar & Schlichting, 2016



Single collision can easily reduce the envelope-to-core-mass ratio by factors of two or more

See also Liu et al. 2015

Take Home Points II

Single collision can easily reduce the envelope-to-core-mass ratio by factors of two or more, leading to increase in observed mean density by factors of ~2-6

Lower limit because of additional loss due to hydrodynamic escape, photo-evaporation and hit-and-run collisions (Liu et al 2015, Hwang, et al. 2017).

Small number of Giant Impacts can give rise to a large diversity in exoplanet densities

Especially attractive explanation for diverse bulk densities observed in multiple planet systems: e.g. Kepler-11, Kepler-20, Kepler-36, Kepler-48, and Kepler-68