Impacts and the Delivery & Erosion of Volatiles

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The Origins of Volatiles in Habitable Planets: The Solar System & Beyond

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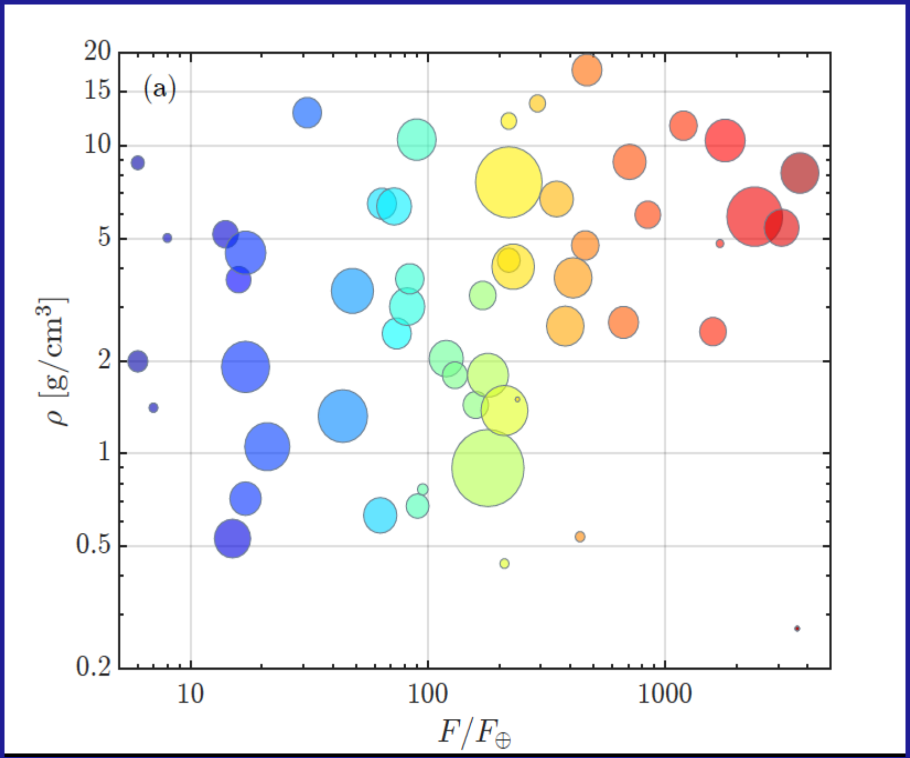
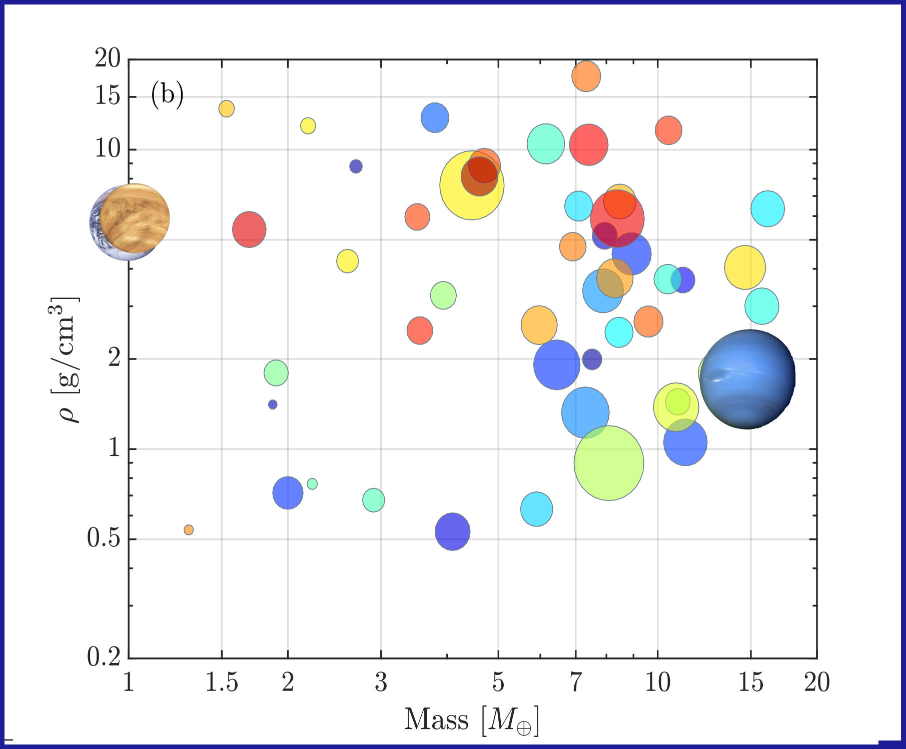
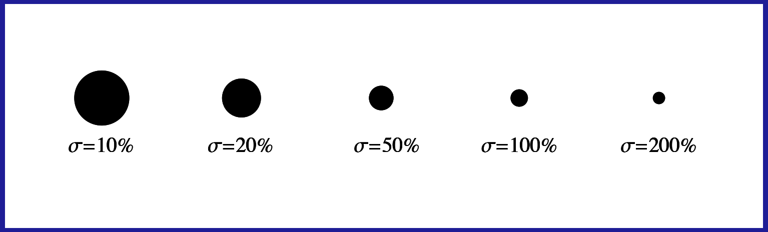
Exoplanet Densities



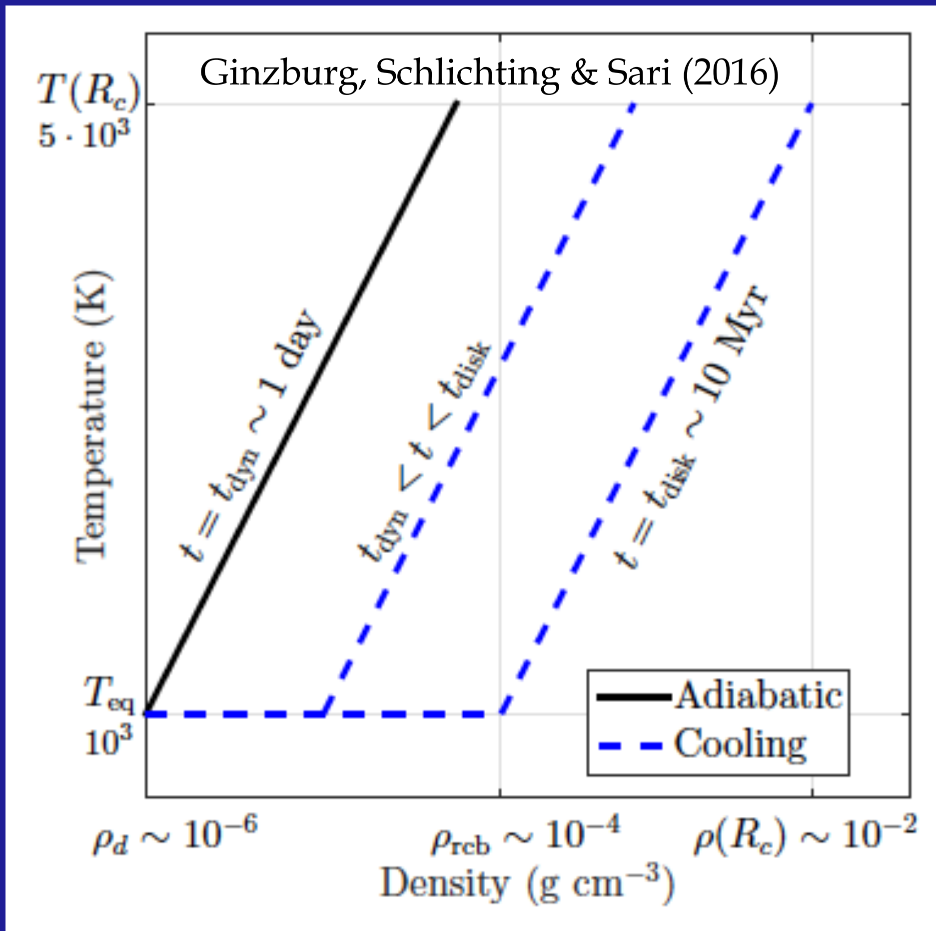


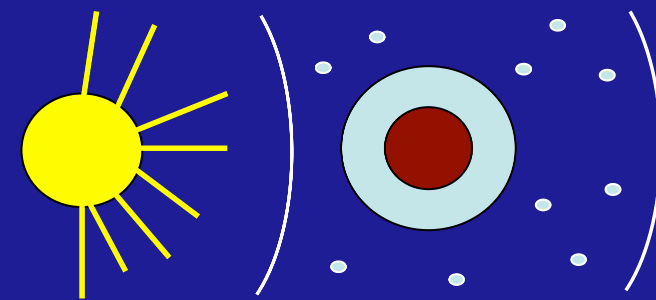


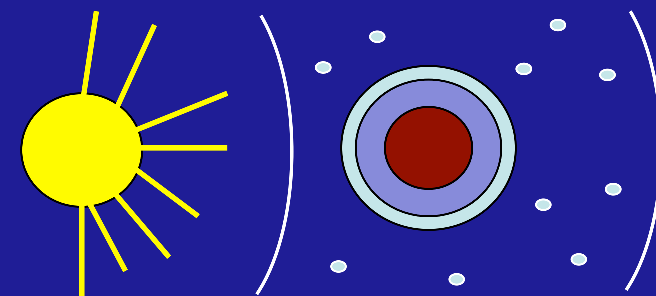
Inamdar & Schlichting 2016

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

Envelope Accretion:





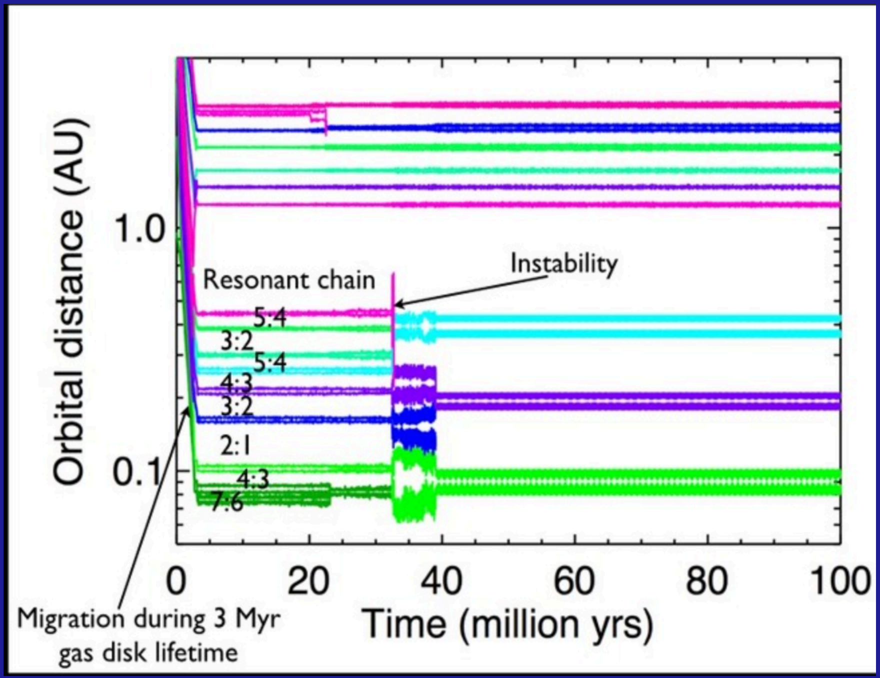


Accretion limited by cooling
(e.g. Inamdar & Schlichting (2015), Lee & Chiang (2015))

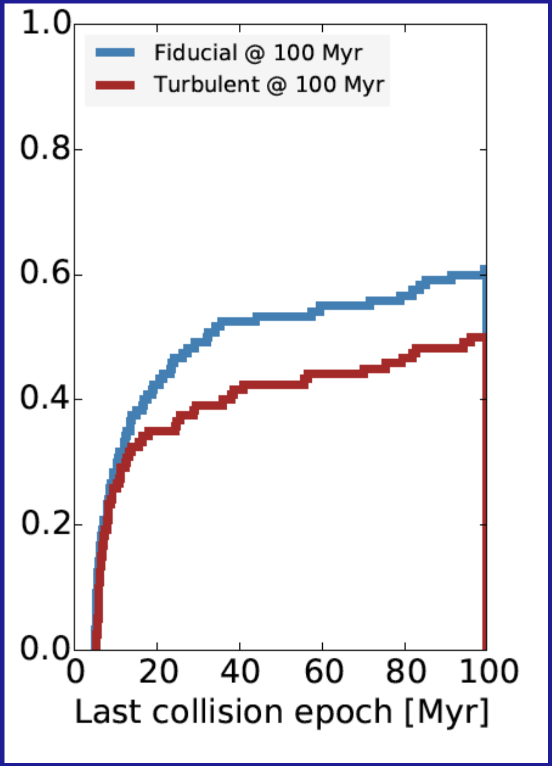
$$f \approx 0.02 \left(\frac{M_c}{M_\oplus}\right)^{0.8} \left(\frac{T_{\rm eq}}{10^3\ {\rm K}}\right)^{-0.25} \left(\frac{t_{\rm disk}}{1\ {\rm Myr}}\right)^{0.5}$$

f only depends logarithmically on $\rho_{\rm disk}$

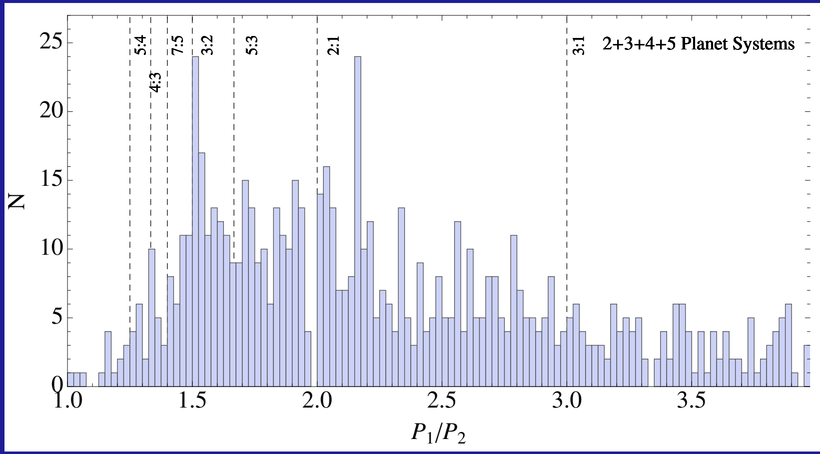
Late Collisions & Kepler Multiple Planet Systems



Cossou et al. 2014



Izidoro et al. 2017



4175 Planetary Candidates

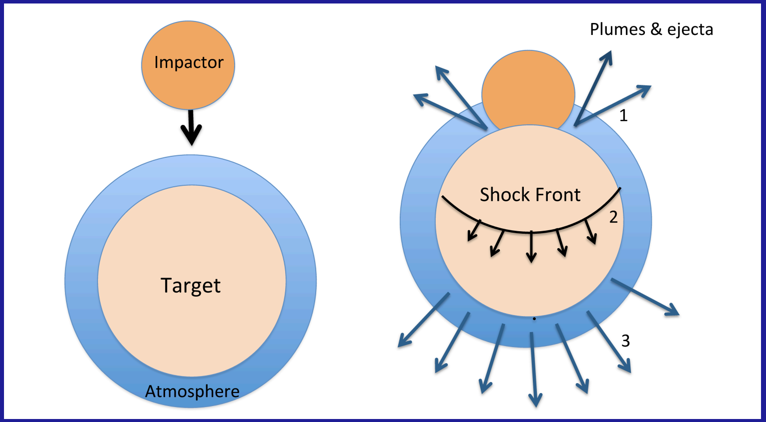
1218 Planets in Multi-Planet Systems

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.

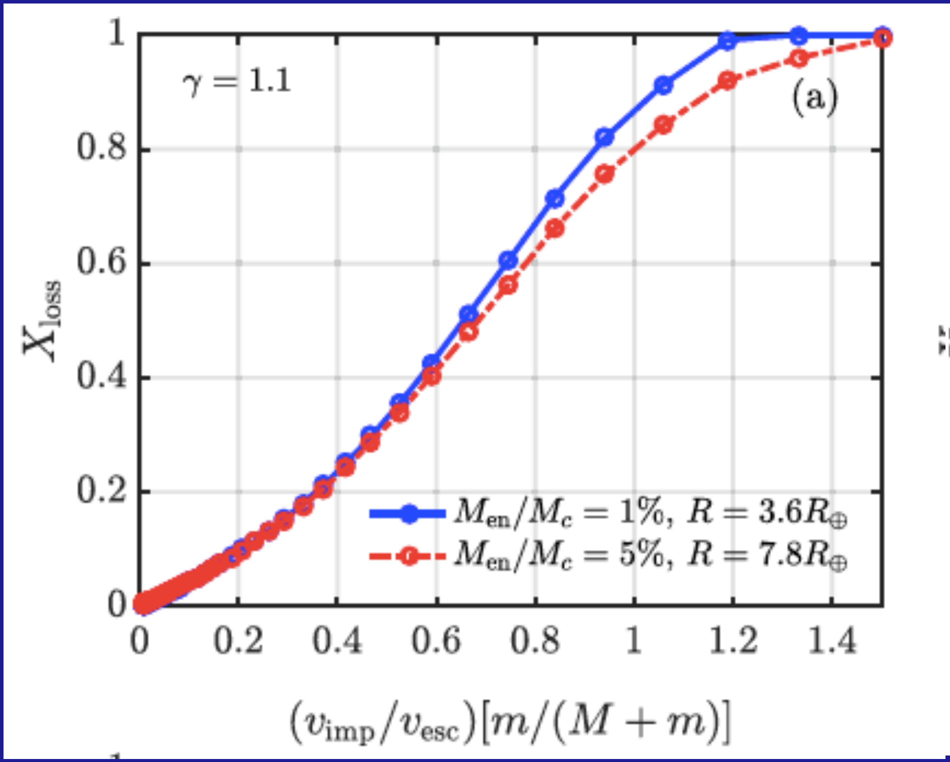
Thermal part

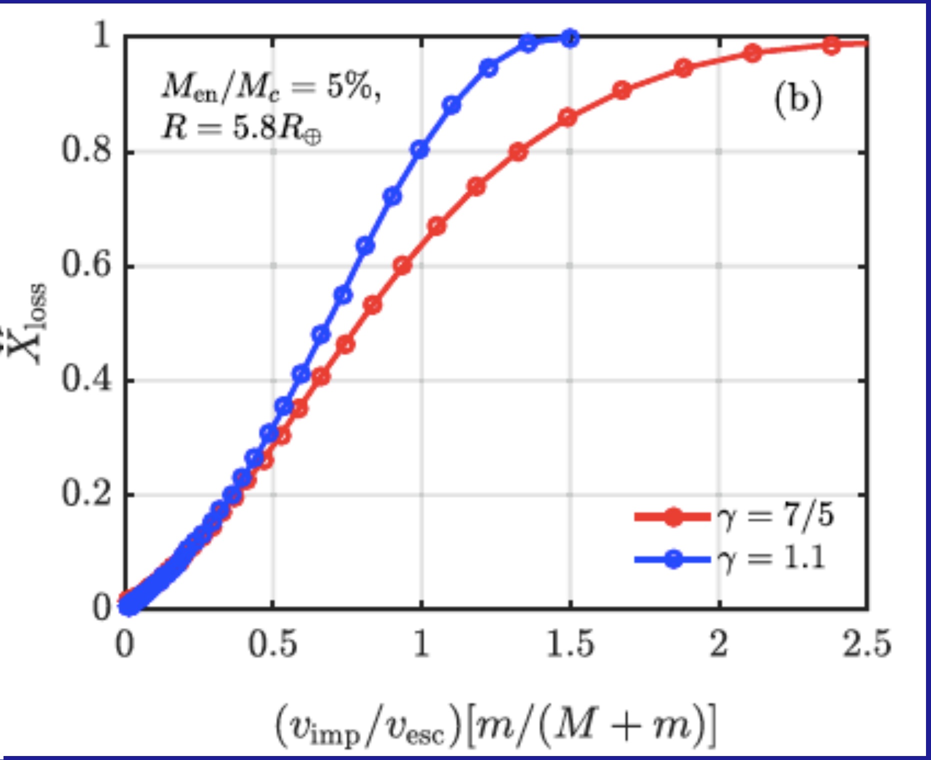
i) The impact heats the core.

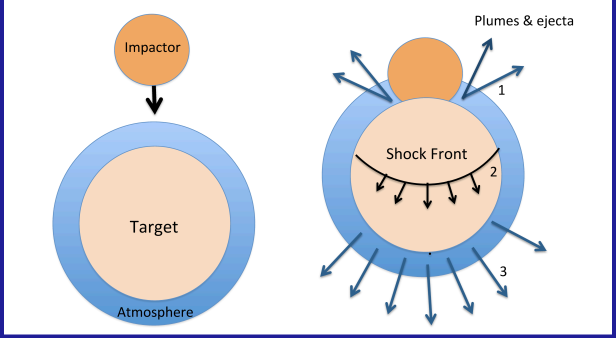
ii) The core exchanges heat with the envelope.

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

Envelope loss due to Giant impacts





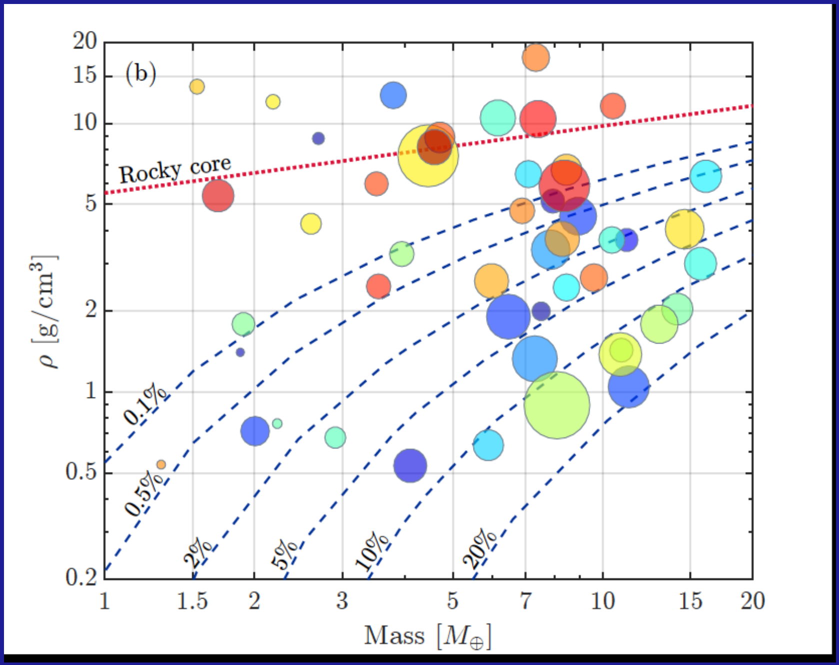


Inamdar & Schlichting, 2016

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

See also Liu et al. 2015

Bulk density change due to Giant Impacts



Inamdar & Schlichting, 2016

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).

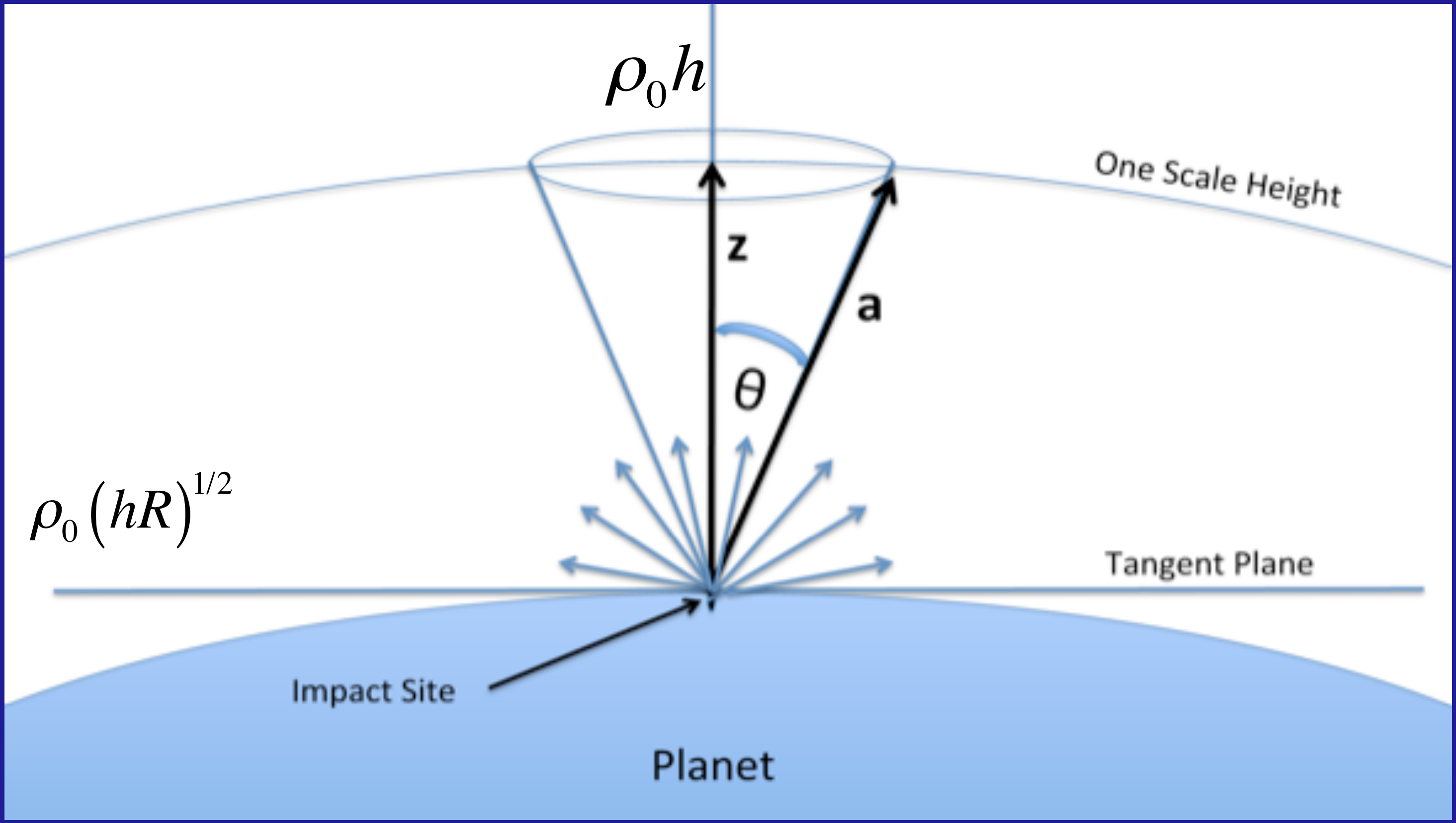
Small number of Giant Impacts can give rise to a large diversity in exoplanet densities

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

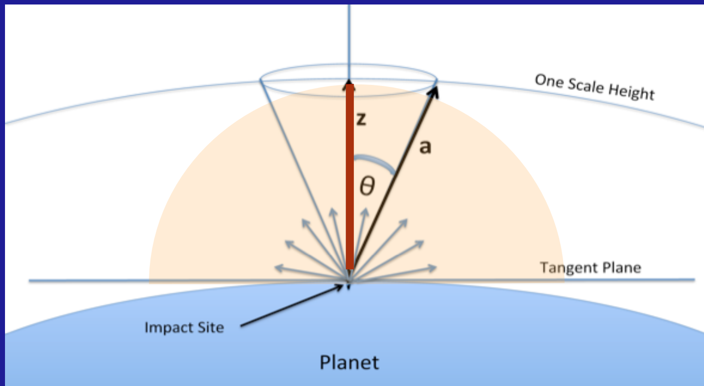
Planetesimal Impacts

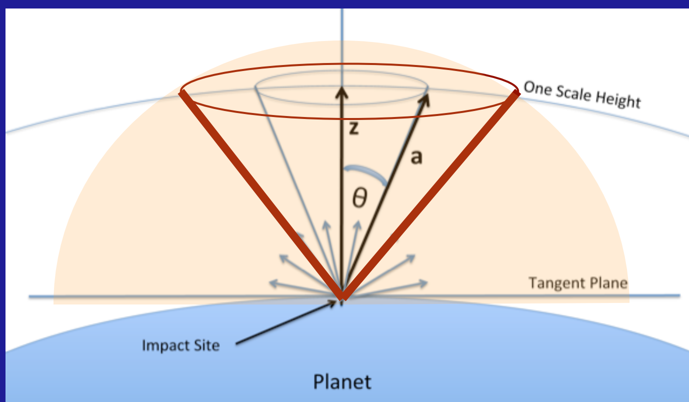
1) Only eject atmosphere locally, h/2R, – but numerous small impacts

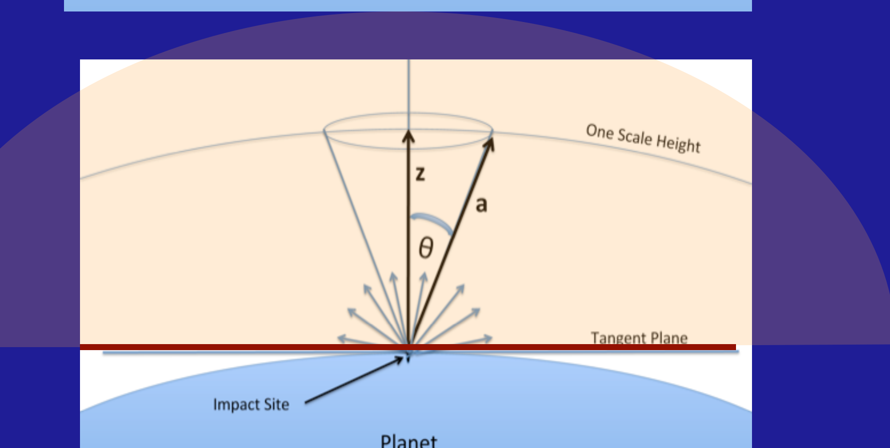
2) Atmosphere is ejected where its mass per unit solid angle is less than of the ejecta, $m_{imp}/2\pi$. (e.g. Melosh & Vickery 1989, Zahnle et al. 1990, Schlichting et al. 2015)



Point-like explosion on the surface, where a mass equal to the mass of the impactor propagates isotropically into a half-sphere with velocity of order the escape velocity.







Atmosphere is ejected only where its mass per unit solid angle is less than of the ejecta, $m_{imp}/2\pi$.

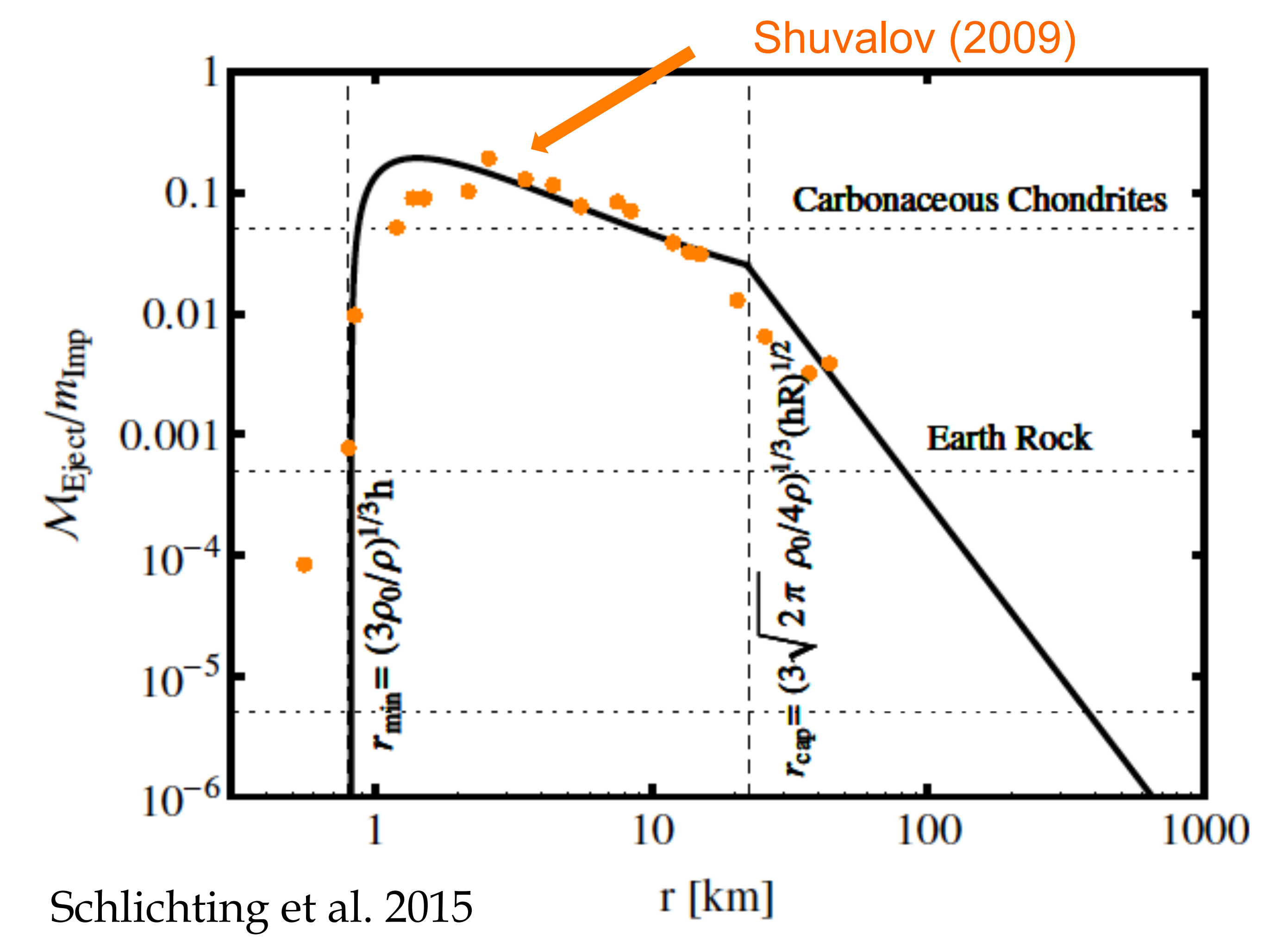
Smallest Impactor Size that can remove any atmosphere:

$$r_{\min} \approx \left(\frac{\rho_0}{\rho}\right)^{1/3} h \sim 1km$$

Smallest Impactor Size that can remove all atmosphere above tangent plane:

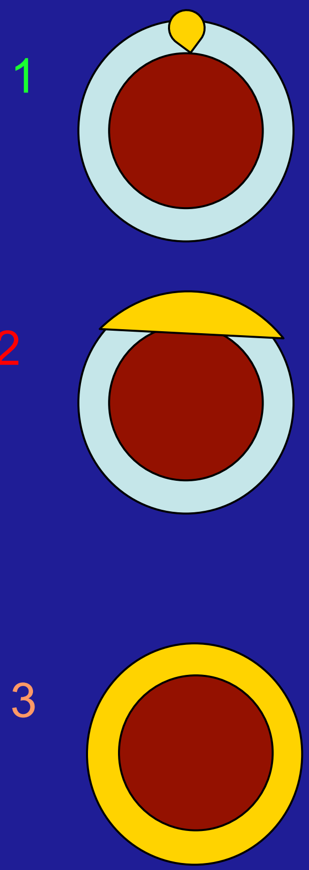
$$r_{cap} \approx \left(\frac{\rho_0}{\rho}\right)^{1/3} (hR)^{1/2} \sim 25km$$

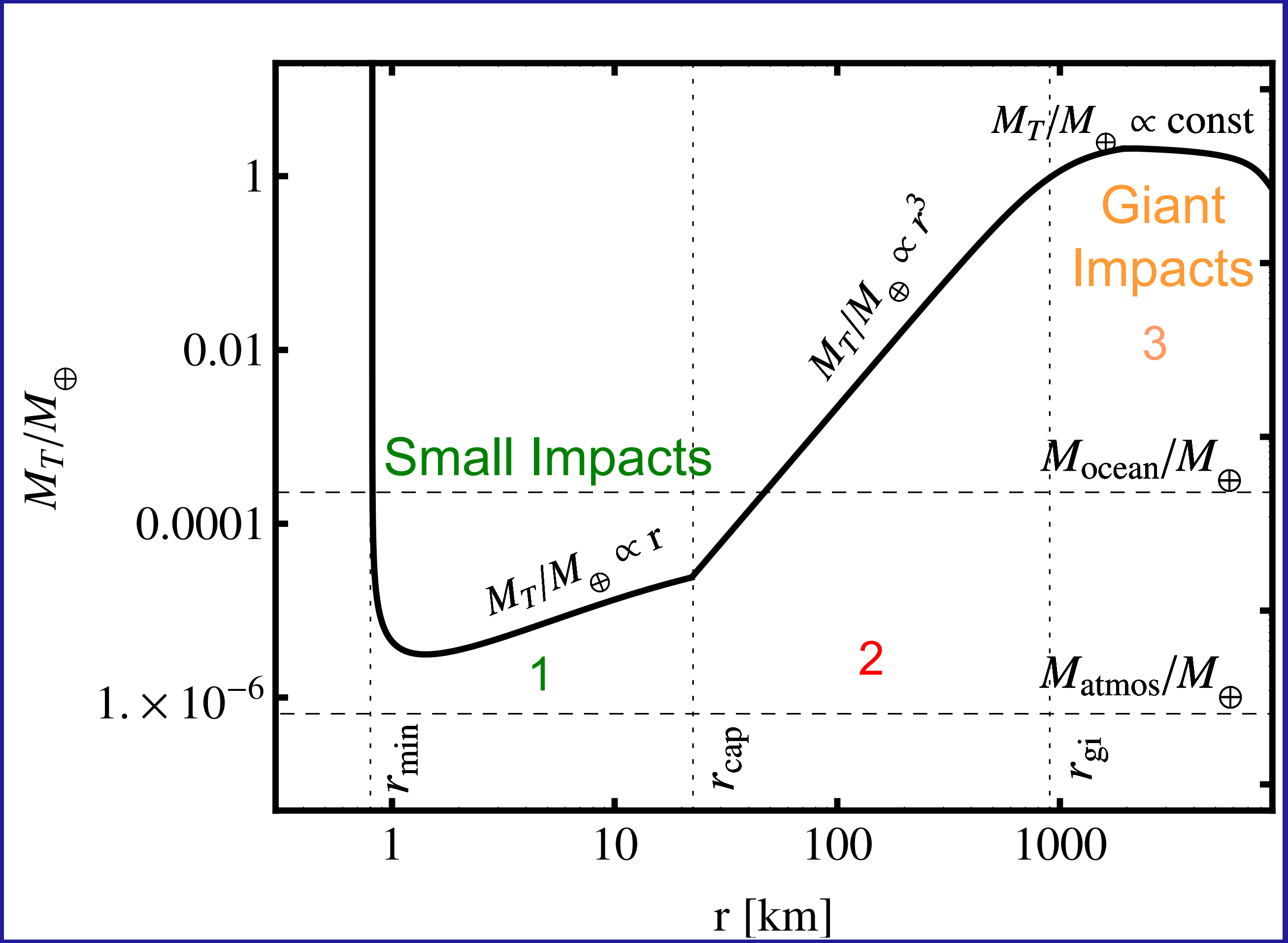
Comparison of analytic and numerical results



Earth's atmosphere may have resulted from equilibrium between atmospheric erosion and volatile delivery from planetesimal impacts.

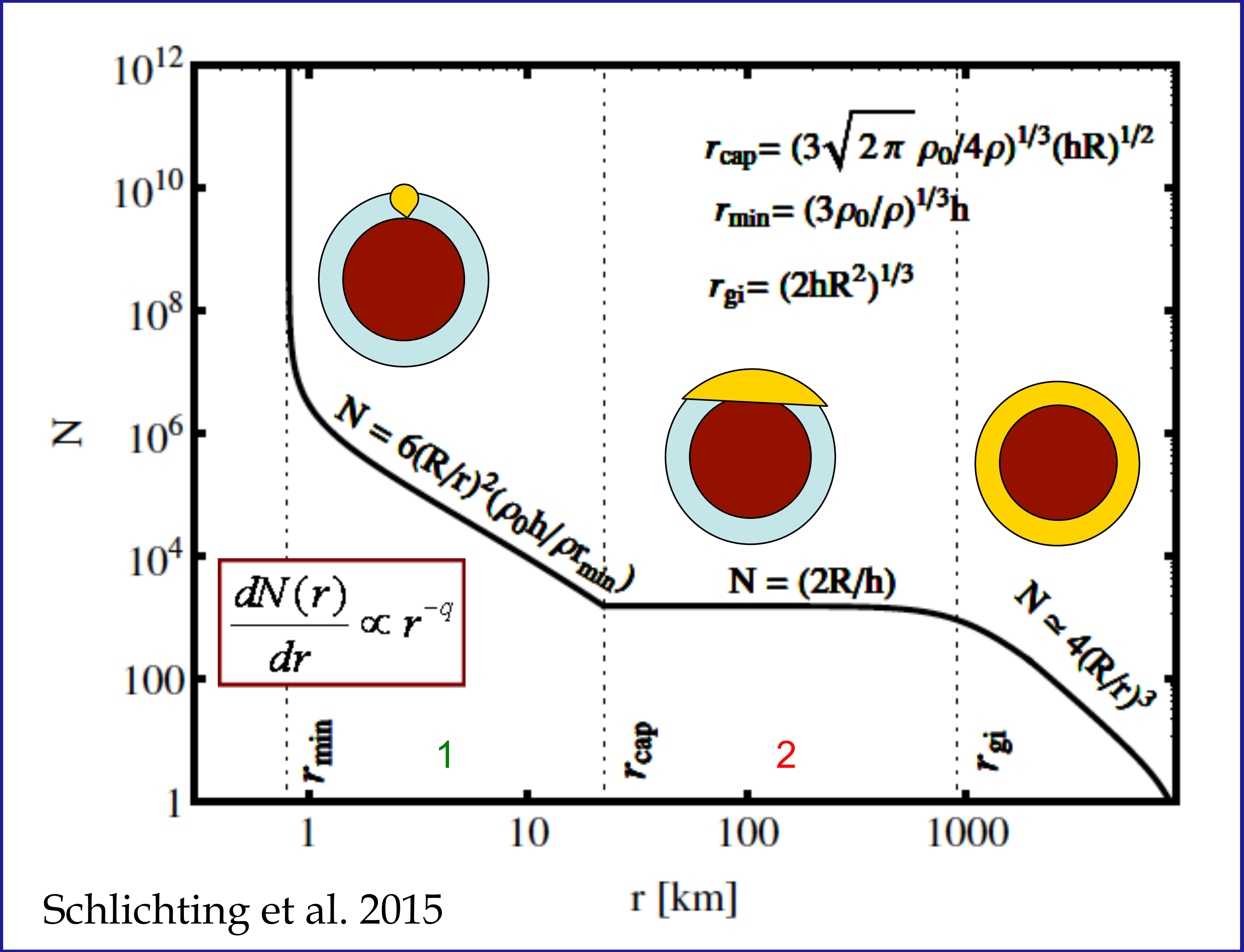
Atmospheric Mass Loss Efficiency for current Earth





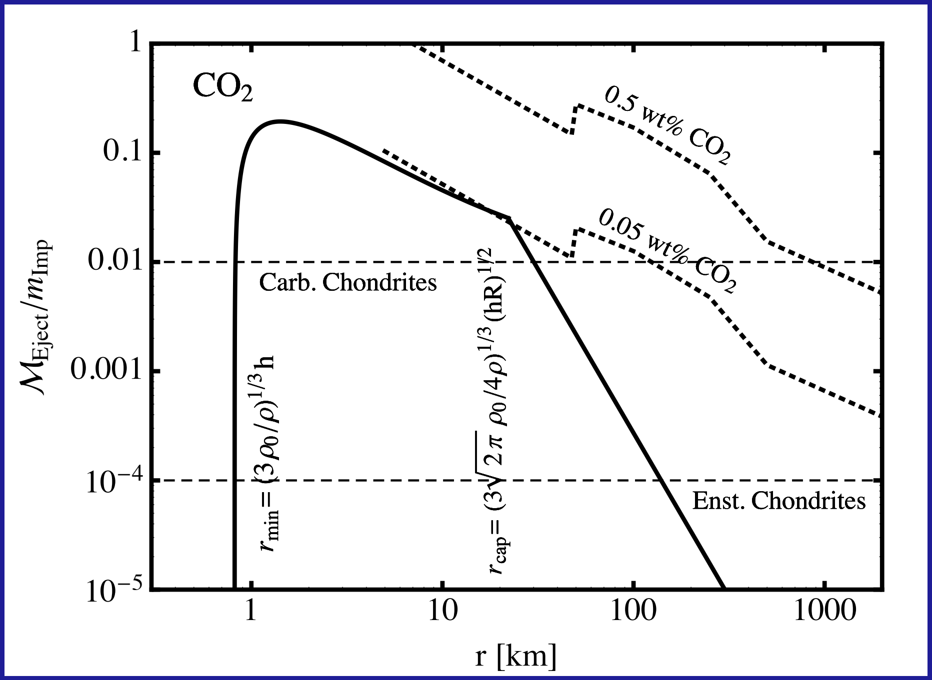
Schlichting et al. 2015

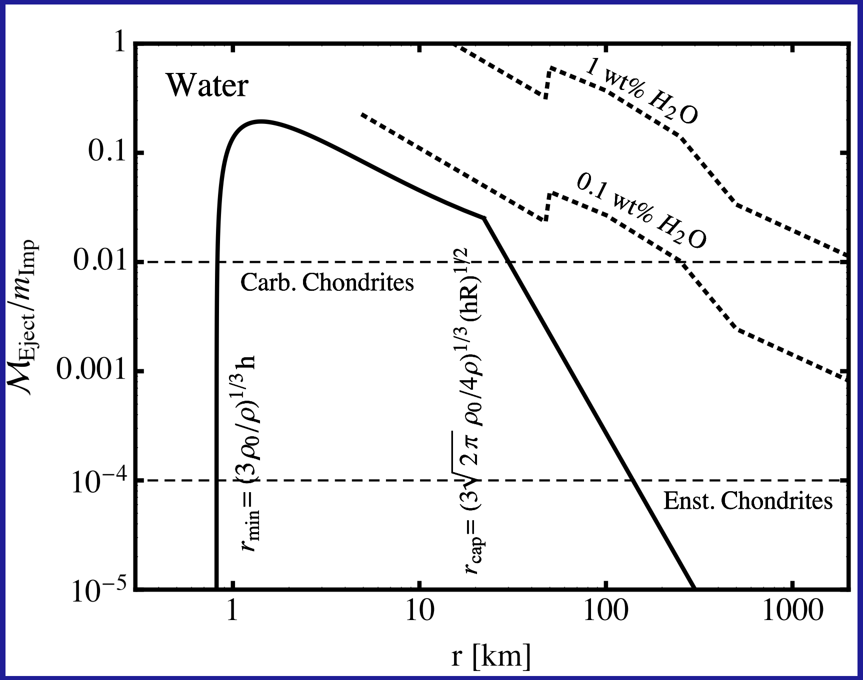
Planetesimal impacts likely dominated the atmospheric mass loss over the formation history of the terrestrial planets.



Regime 1) dominates for q>3, Regime 2) dominates for 1 < q < 3

Volatile delivery and atmospheric erosion due to planetesimal impacts





Whether or not the Earth's atmosphere is eroded or grown during the late accretion phase depends critically on the initial volatile content of the mantle at the end of the magna ocean phase after the last giant impact (Elkins-Tanton 2008, Black et al. 2012) and the volatile content of the impactors.

Summary

- Planetesimal impacts likely dominated the atmospheric mass loss over the formation history of the terrestrial planets. For complete loss need planetesimals: M=M_atmos, Giant Impacts: M=M_core

- 0.1-0.5% of Earth masses in small impactors, which is about the mass inferred for the late veneer, can erode the entire Earth's atmosphere. Atmospheric erosion is a runaway process.

- Earth’s early atmosphere could have resulted from equilibrium between atmospheric erosion and volatile delivery from planetesimal impacts + outgasing. Planetsimals dominate the atmospheric loss, Giant Impacts dominate the outgasing.