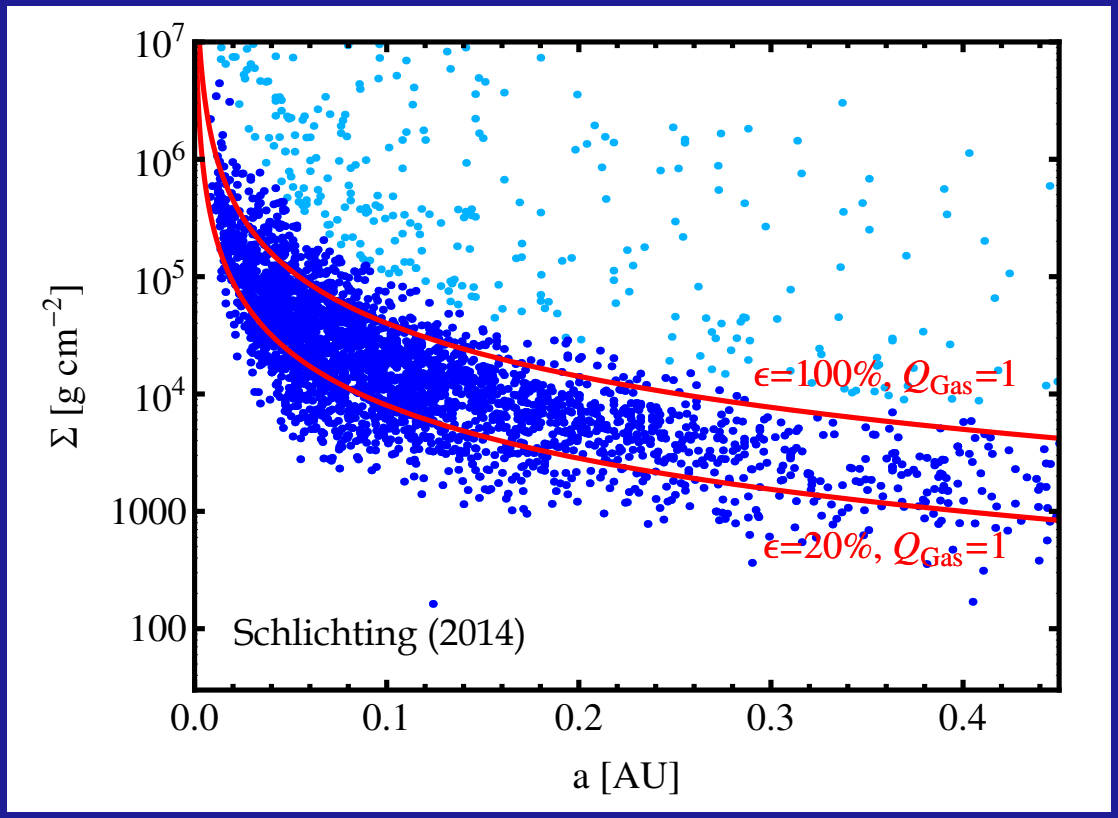
Lecture: The Role of Impacts

Summer School 2015

Professor Schlichting (MIT)

7th August 2015

Forming Close-In Planets as Isolation masses



R > 5 R_{Earth}

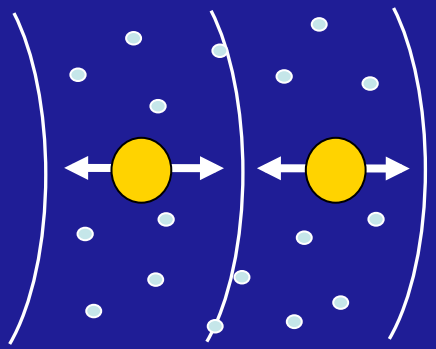
R < 5 R_{Earth}

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

(Toomre 1964)

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

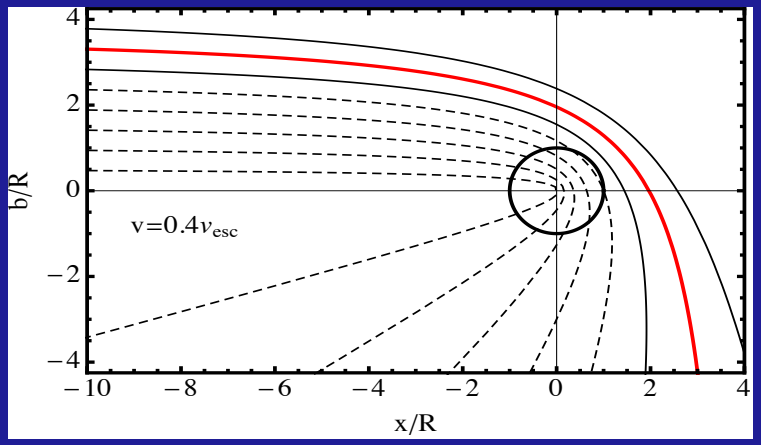
$$\Delta a \sim 2 v_H / \Omega$$



Viscous Stirring

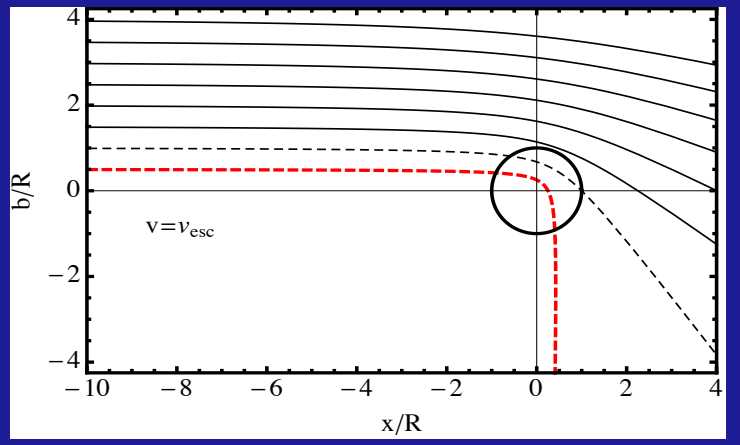
Viscous stirring tends to increase the random kinetic energy all all bodies in the disk

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



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

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



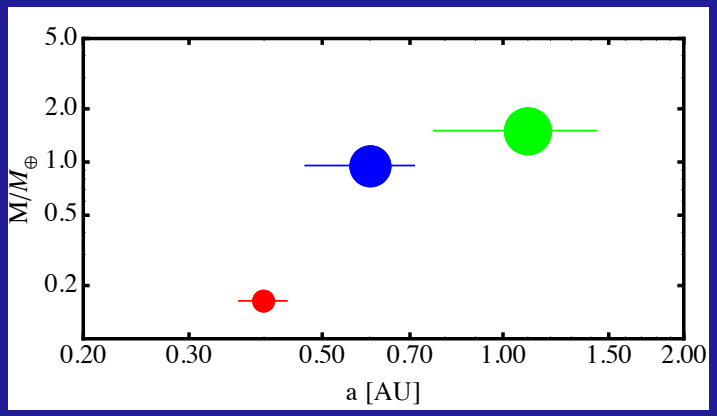
$$\sigma_{coll} \sim \pi R^2 \left(1 + \left(\frac{v}{v_{esc}} \right)^{-2} \right)$$

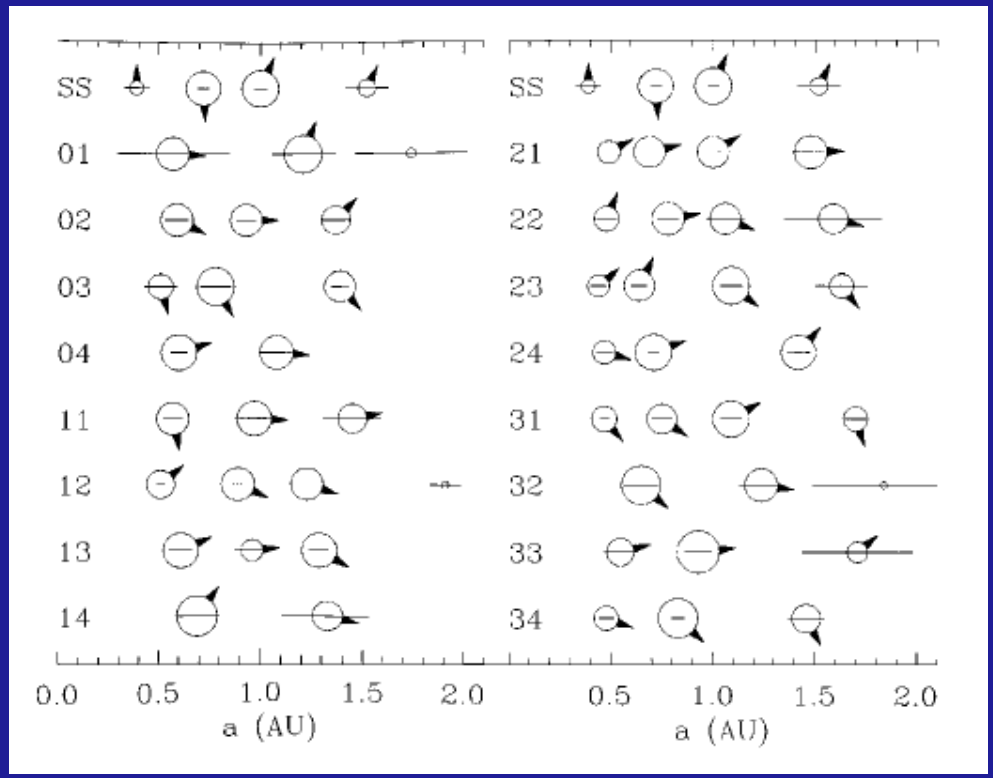
Example: Terrestrial Planets

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

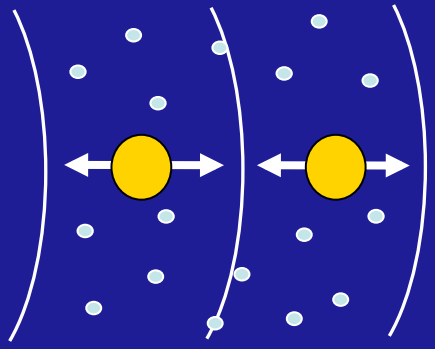
$M_{planet} \Longleftrightarrow \Sigma$

Schlichting 2014



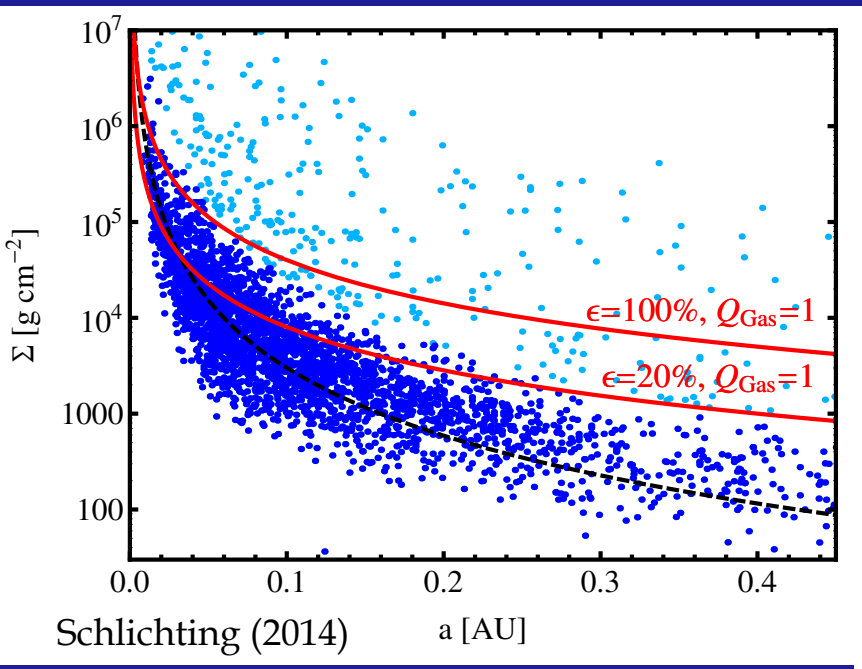


$\Delta a \sim 2 v_{esc} / \Omega$

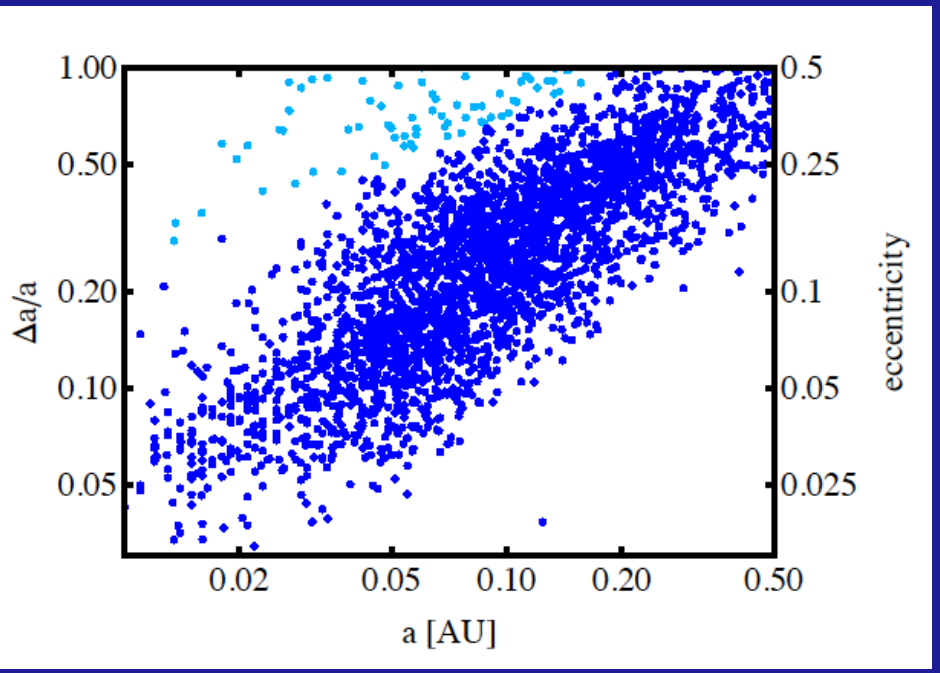


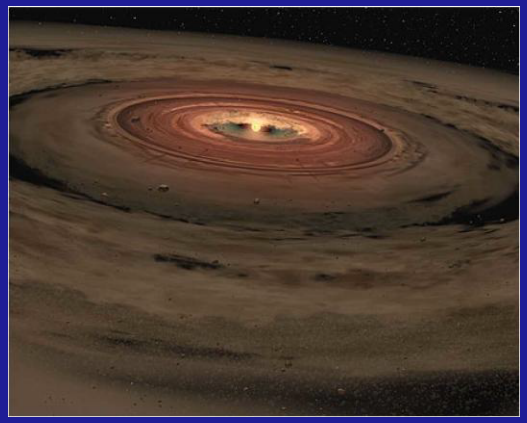
Chambers 2001

Forming Close-In Planet with Giant Impacts

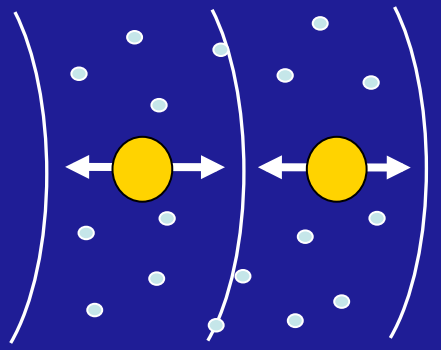


Schlichting (2014)

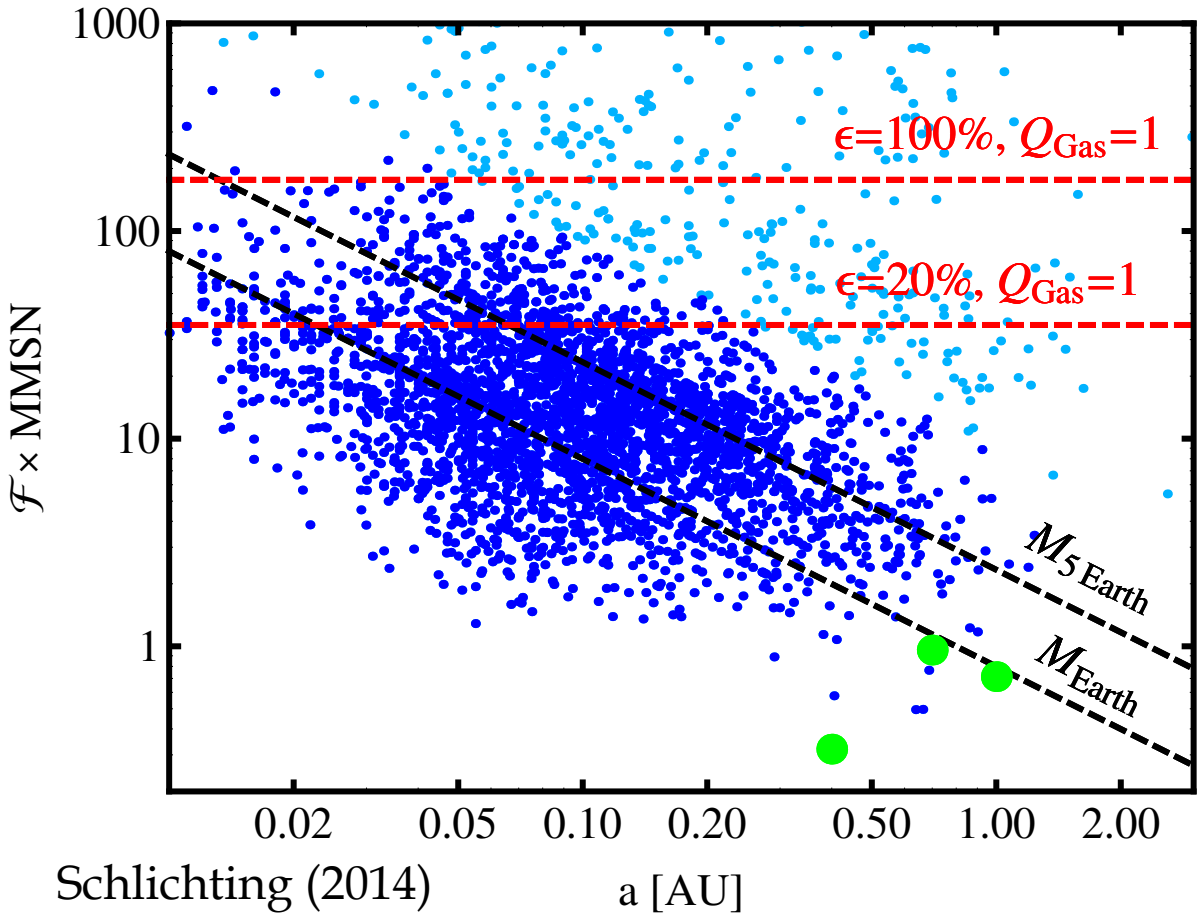


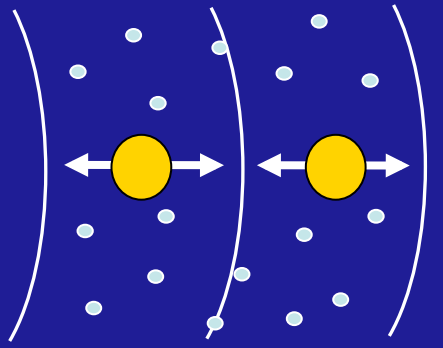


$$\Delta a \sim 2 v_{esc} / \Omega$$



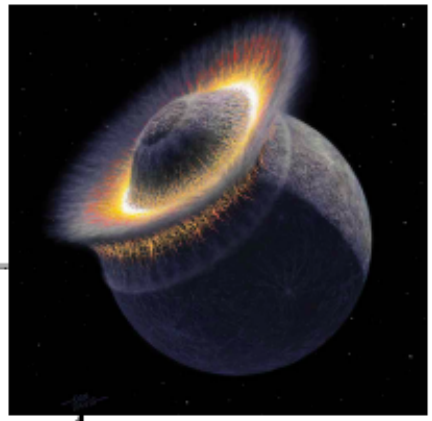
Minimum Disk Masses Required

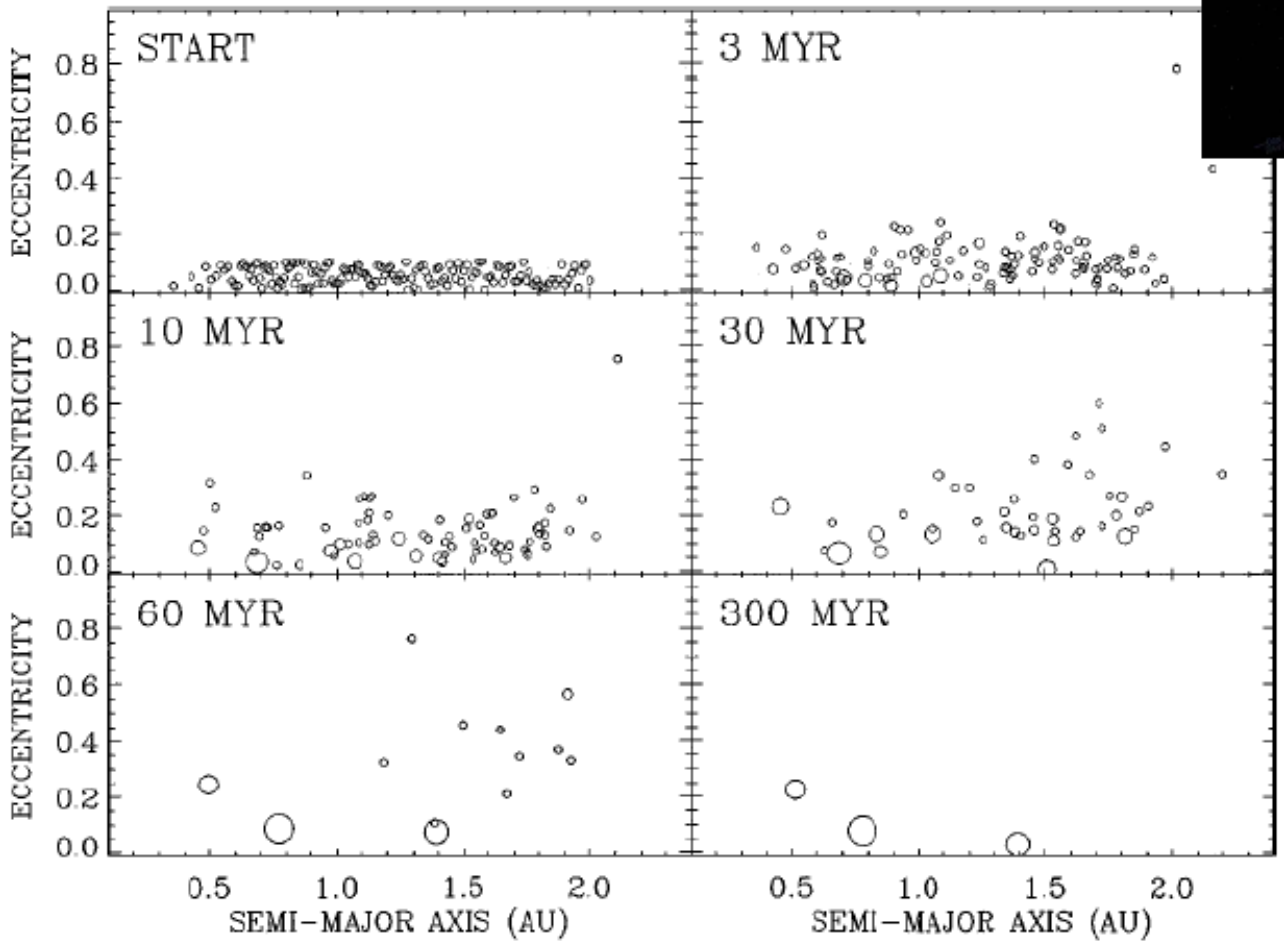




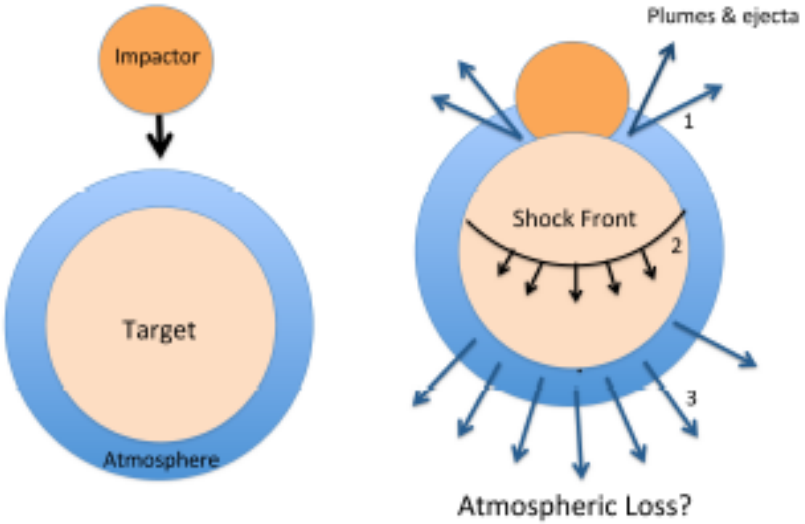
MMSN type disks consistent with formation further out and subsequent inward migration and/or radial inward drift of solids and subsequent local assembly.

Giant Impacts

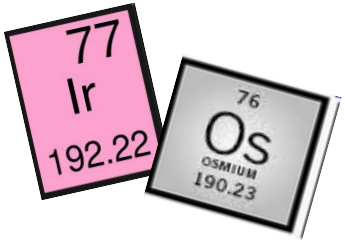


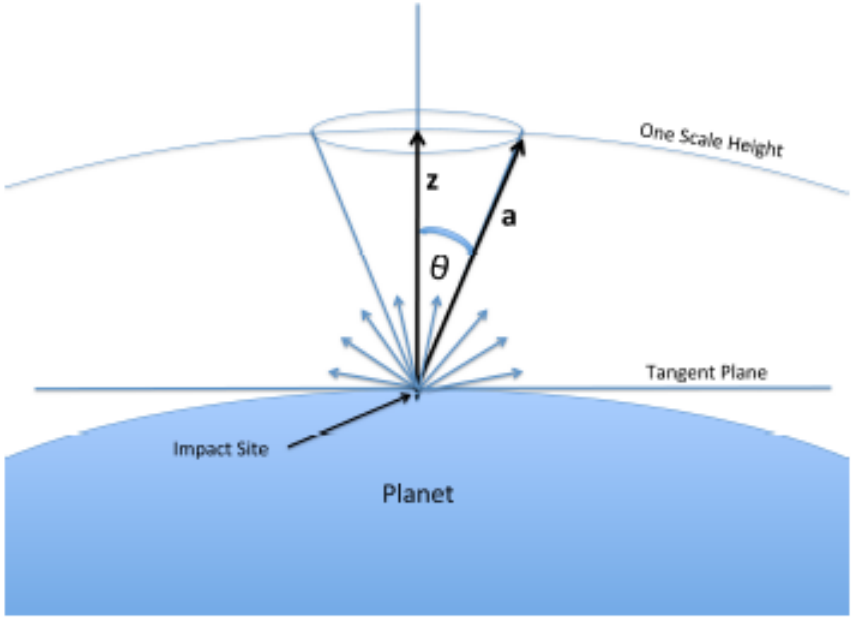


Chambers 2002



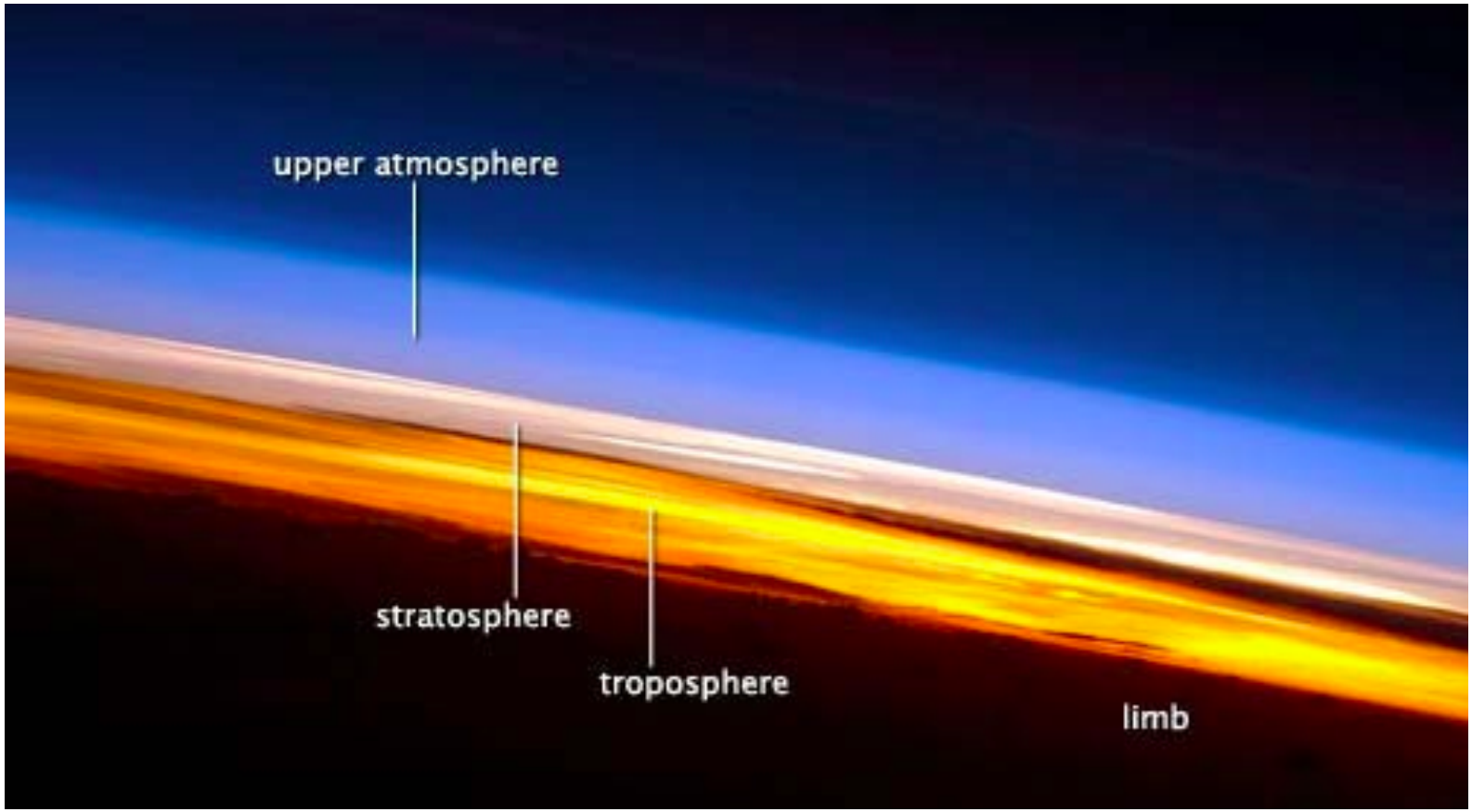
Giant Impacts





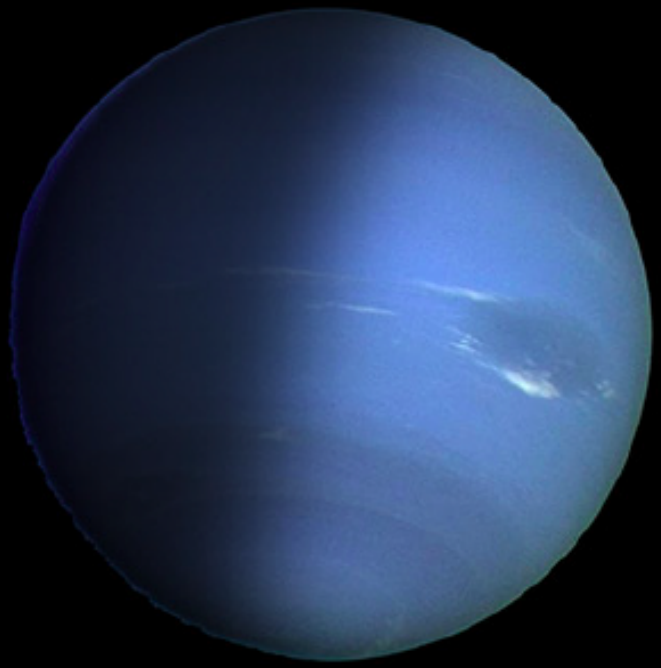
Planetesimal Impacts

Impacts & Terrestrial Planet's Atmospheres



How Do Planets Acquire Their Atmospheres?

Gas Giants



Primordial: hydrogen-rich gas accreted directly from protoplanetary disk.

Super-Earths

What happens at intermediate masses?

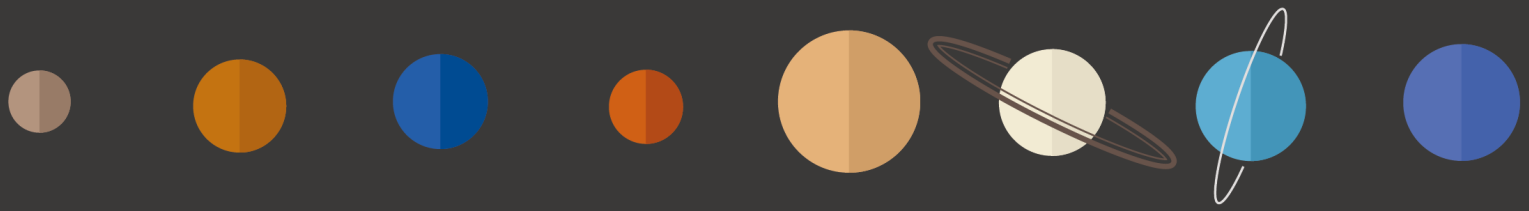
Terrestrial

Outgassed: melting of solids releases gas into atmosphere.

Depletion of light elements

Knutson et al. 2015

ATMOSPHERES OF THE SOLAR SYSTEM



The Terrestrial Planets

MERCURY

Pressure: ~10^{-14} atm

- O_2 OXYGEN 42%
- Na SODIUM 29%
- H_2 HYDROGEN 22%
- OTHER GASES 7% He, K, Ar, CO_2, H_2O, N_2, Xe, Kr & Ne

VENUS

Pressure: ~90 atm

- CO_2 CARBON DIOXIDE 96%
- N_2 NITROGEN 3%
- OTHER GASES 1% SO_2, Ar, H_2O, CO, He & Ne

CLOUDS OF SULFURIC ACID

EARTH

Pressure: ~1 atm

- N_2 NITROGEN 78%
- O_2 OXYGEN 21%
- Ar ARGON ~1%
- OTHER GASES <1% CO_2, Ne, He, CH_4, Kr & H_2

MARS

Pressure: ~0.006 atm

- CO_2 CARBON DIOXIDE 95%
- N_2 NITROGEN 3%
- Ar ARGON 1.5%
- OTHER GASES 0.5% O_2, CO, H_2O, NO, Ne, Kr & Xe

The Gas Giants

JUPITER

Pressure: >>1000 atm

- H_2 HYDROGEN 90%
- He HELIUM ~10%
- OTHER GASES <1% CH_4, NH_3, C_2H_6, H_2O

HYDROGEN IS METALLIC AT HIGH PRESSURE

SATURN

Pressure: >>1000 atm

- H_2 HYDROGEN 96%
- He HELIUM 3%
- OTHER GASES 1% CH_4, C_2H_6, H_2O

SULFUR GIVES GAS CLOUDS A YELLOW CAST

URANUS

Pressure: >>1000 atm

- H_2 HYDROGEN 83%
- He HELIUM 15%
- CH_4 METHANE 2.5% + Trace gases: HD

METHANE GAS CAUSES URANUS'S BLUE COLOUR

NEPTUNE

Pressure: >>1000 atm

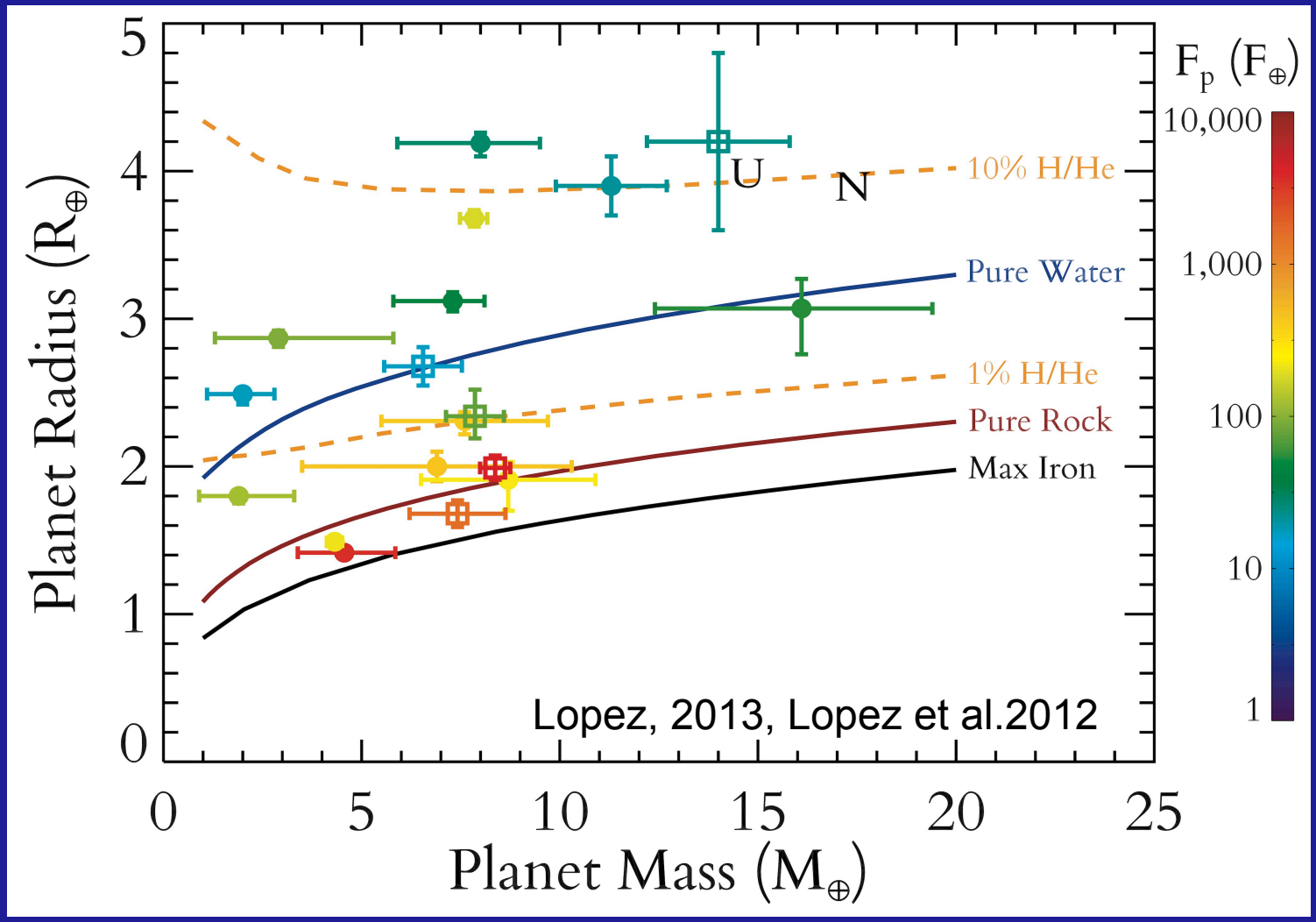
- H_2 HYDROGEN 80%
- He HELIUM 19%
- CH_4 METHANE ~1% + Trace gases: HD, C_2H_6

STRONGEST WINDS IN THE SOLAR SYSTEM

Note: Planet sizes not to scale. Pressures for terrestrial planets are surface pressures. Mercury's atmosphere is not an atmosphere in the strict sense of the word, being a trillion times thinner than Earth's.

Atmospheric compositions taken from NASA, http://quest.arc.nasa.gov/projects/astrobiology/astroventure/challenge/Articles/planetatmoscomp.pdf

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.

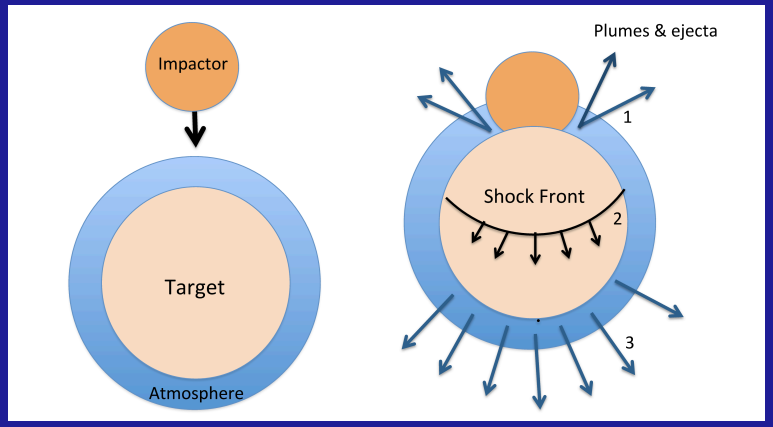
Atmospheric Mass Loss During Planet Formation

1. Giant Impacts

1) The impact launches a strong shock.

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

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

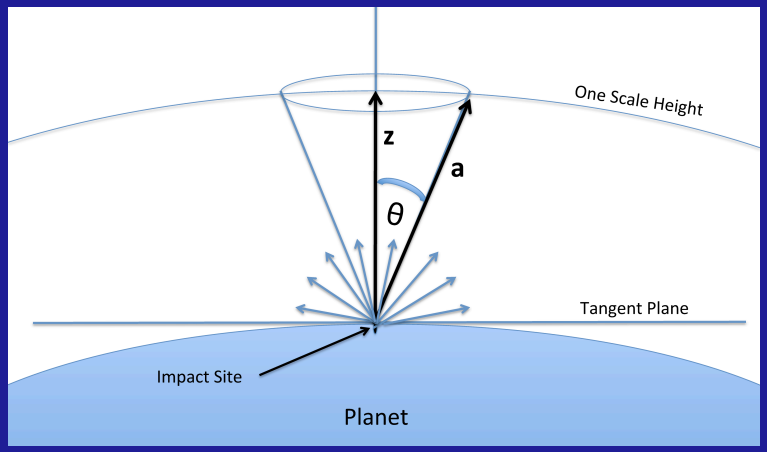


e.g. Genda & Abe 2003, 2005, Schlichting et al. 2015

2. Small Planetesimal Impacts

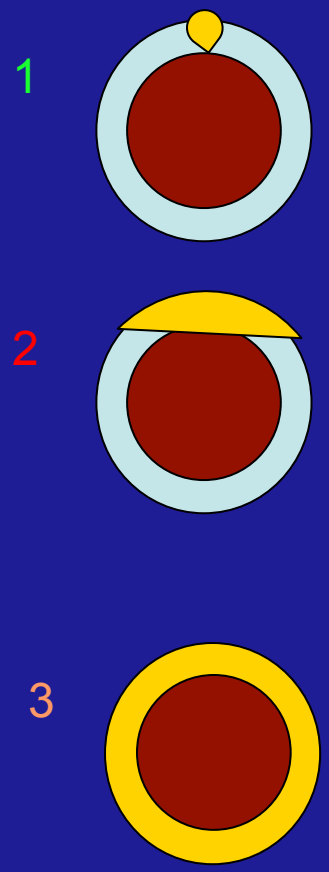
1) Only eject atmosphere locally, h/2R, – but numerous small impacts

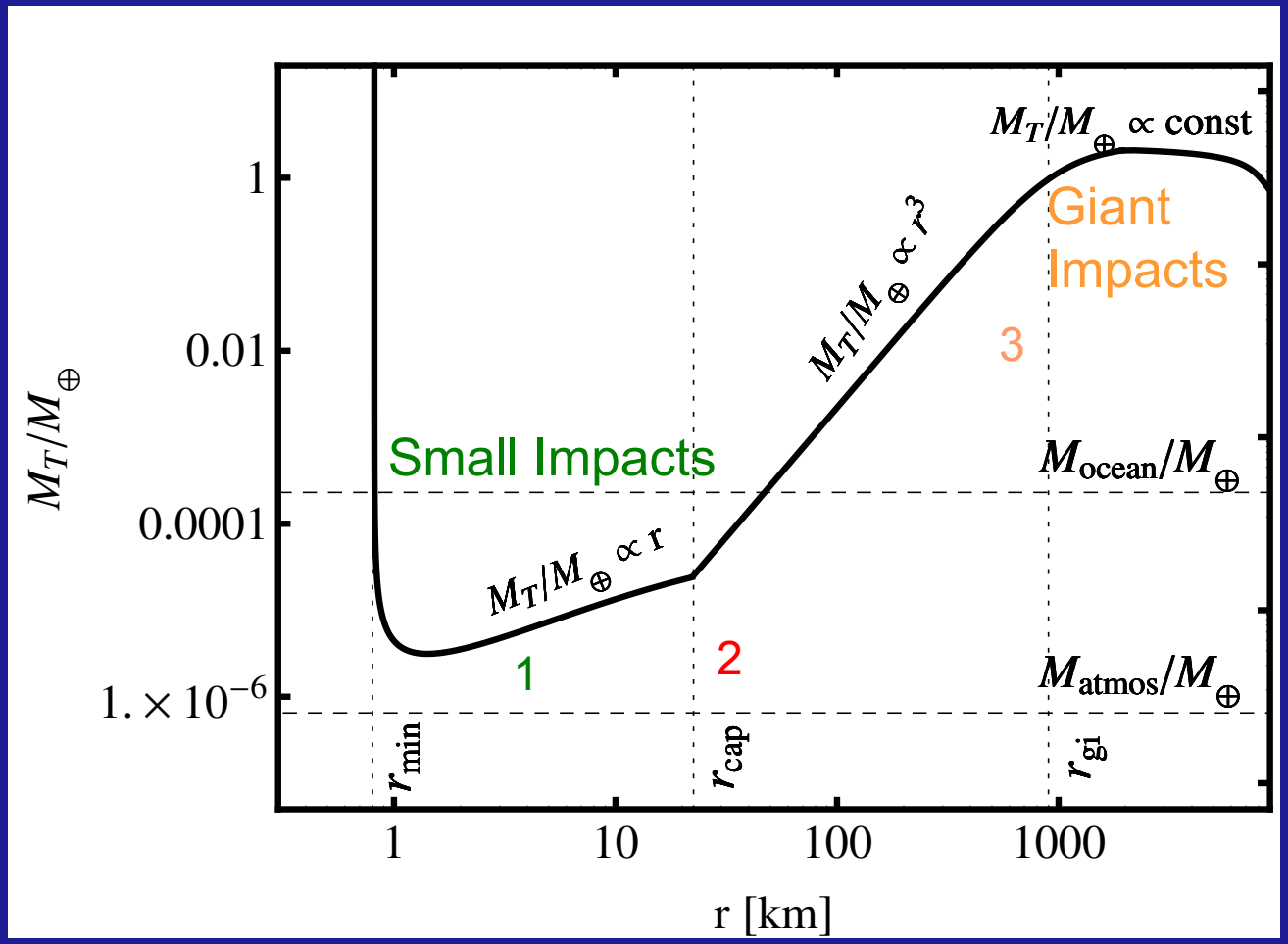
2) Atmosphere is ejected only where its mass per unit solid angle is less than of the ejecta, $m_{imp}/2\pi$.



e.g. Melosh & Vickery 1989, Schlichting et al. 2015

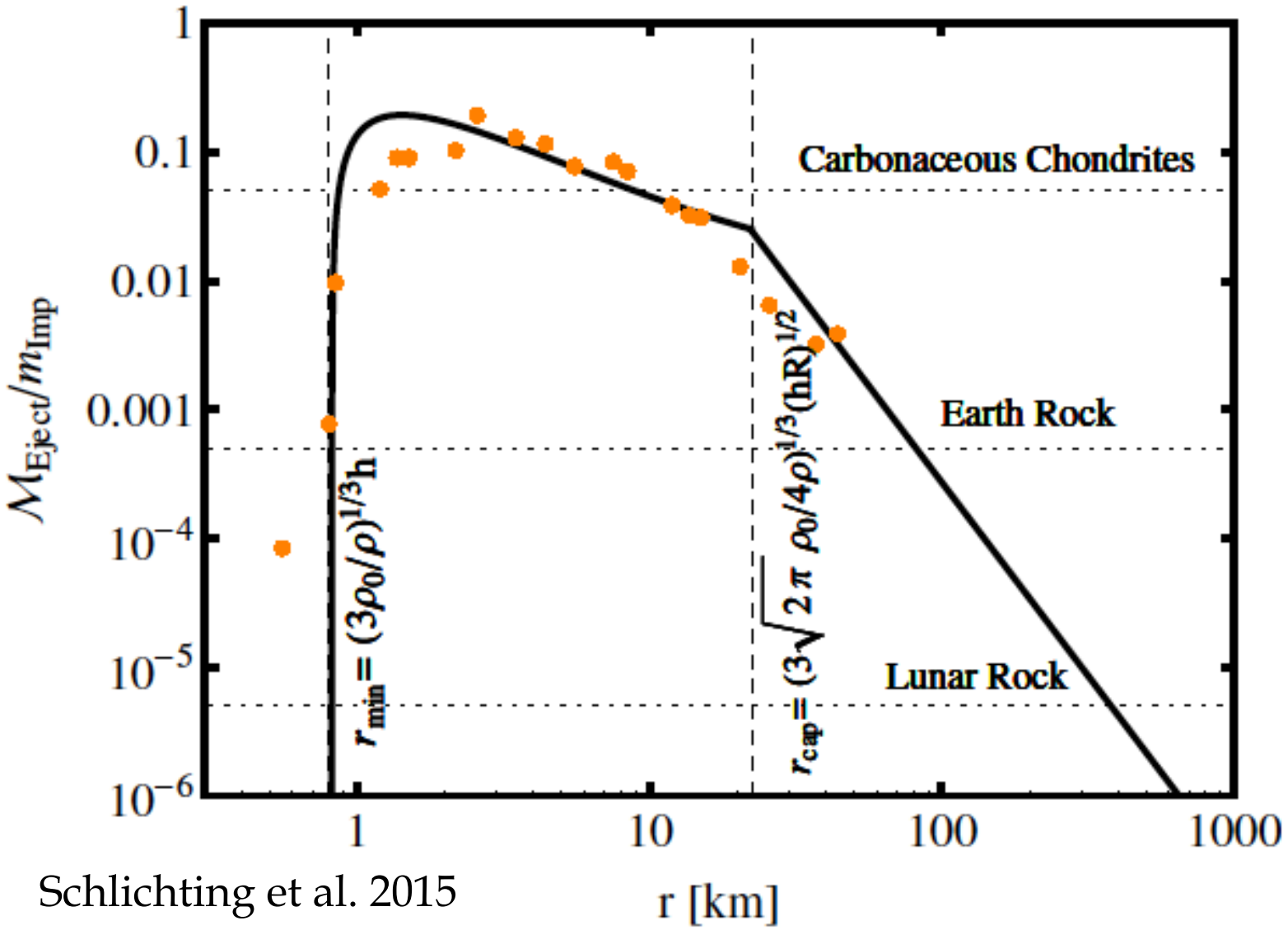
Atmospheric Mass Loss Efficiency for current Earth





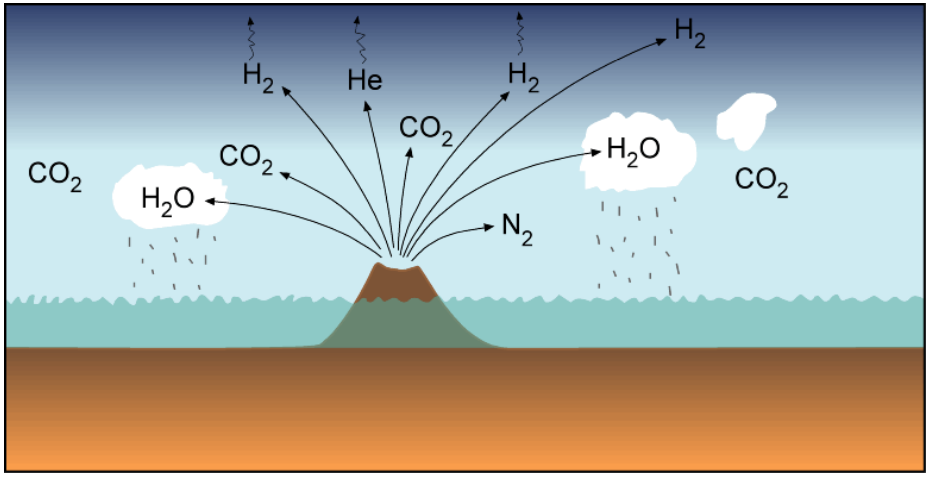
Schlichting et al. 2015

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

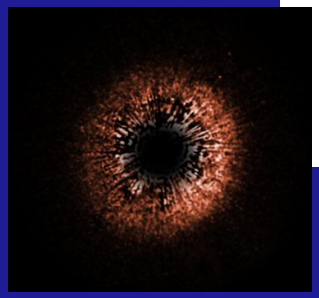


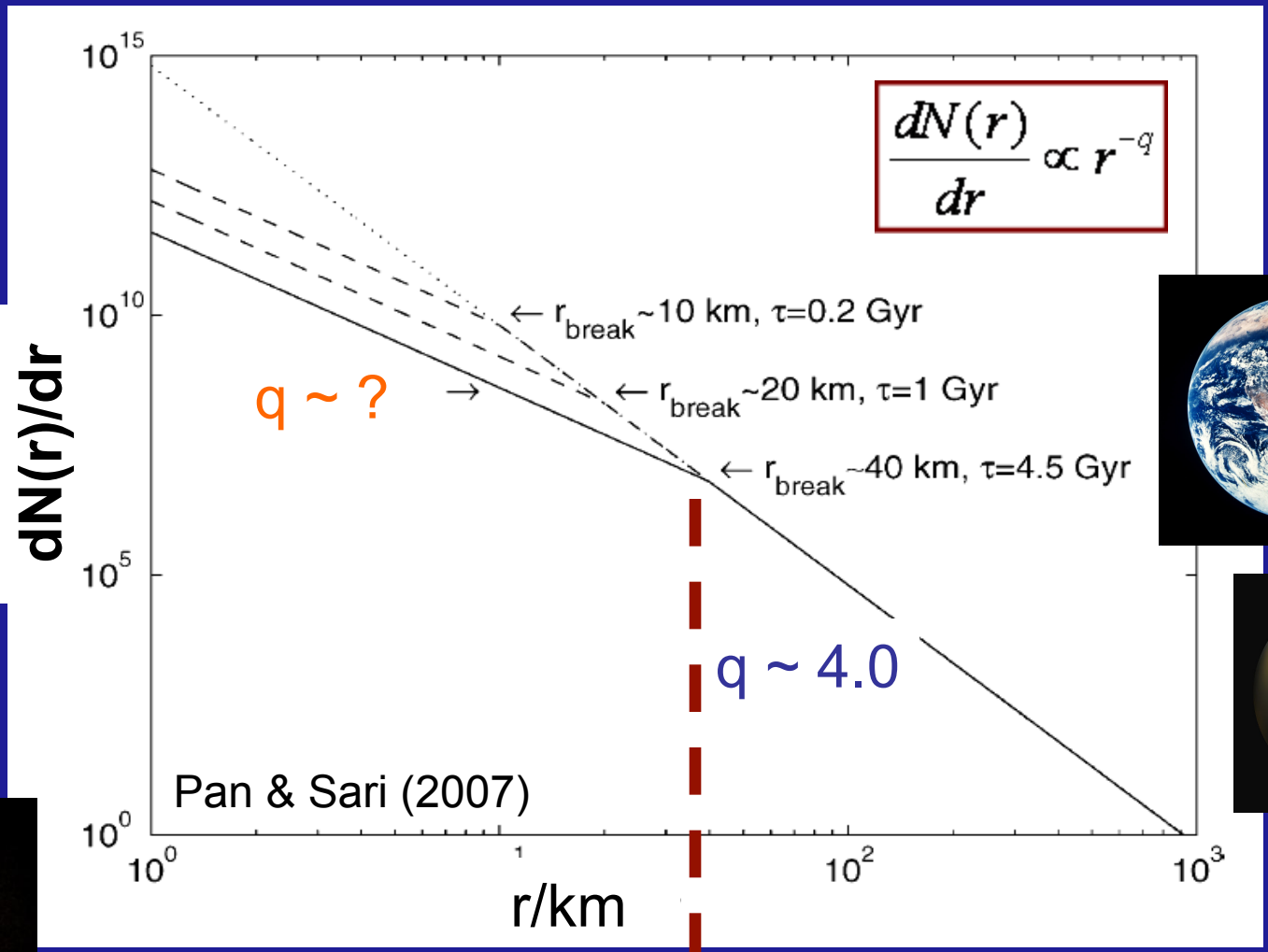
Schlichting et al. 2015

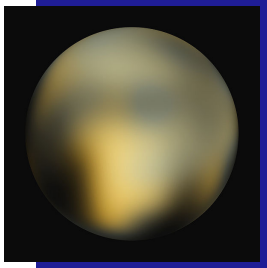
How did the Earth get it’s Ocean?



The Kuiper Belt Size Distribution

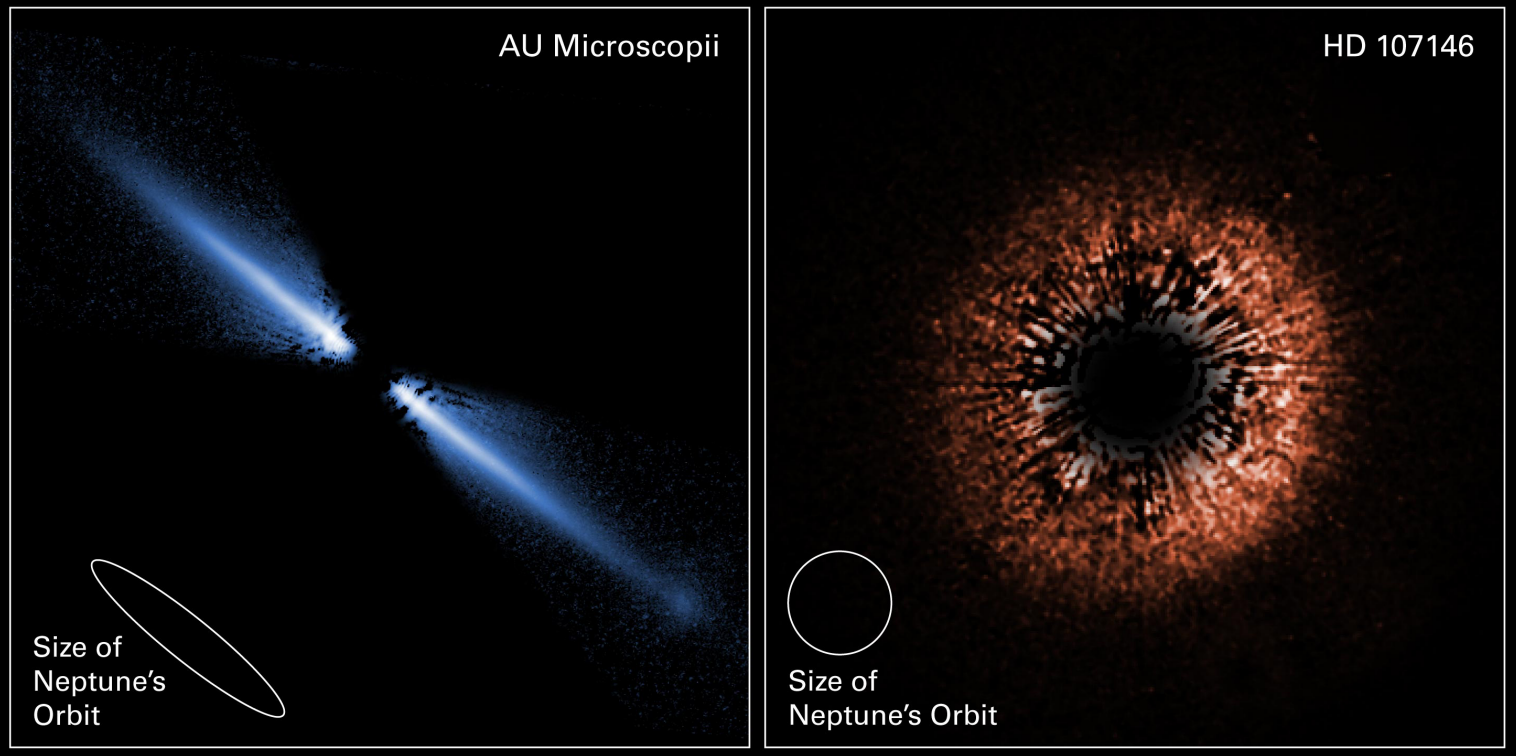






Evolved

Primordial



Circumstellar Debris Disks
Hubble Space Telescope • ACS HRC

NASA, ESA, J. Krist (STScI/JPL), D.R. Ardila (JHU), D.A. Golimowski (JHU), M. Clampin (NASA/Goddard), H. Ford (JHU), G. Hartig (STScI), G. Illingworth (UCO-Lick) and the ACS Science Team

STScI-PRC04-33a

Collisional cascades

Steady state: → Mass conservation

mass rate of destruction

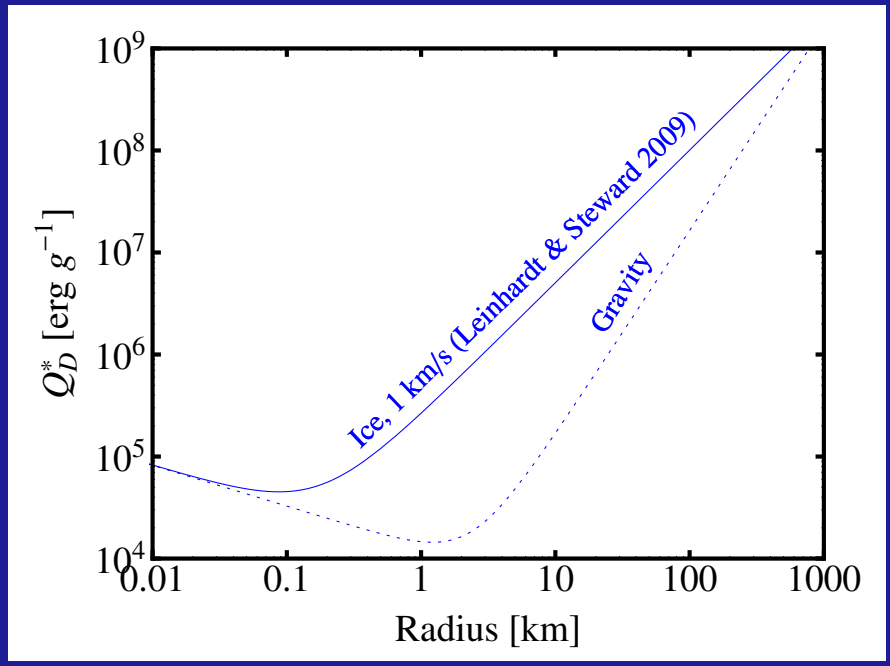
$$\text{constant} = \rho r^3 \cdot \frac{N(r)\, r^2}{\text{area of disk}} \cdot N(r_B(r))\, \Omega$$

target mass

covering fraction of targets

rate of disk crossings by bullets

$$N(r) \propto r^{1-q}$$



Bullet to Target Ratio:

Strength Regime: Dohnanyi (1969)

$$\rho r_B^3 v^2 = Q^* \rho r^3 \rightarrow r_B \propto r \rightarrow q = 7/2$$

Gravity Regime: Pan & Sari (2007)

$$\rho r_B^3 v^2 = \rho r^3 v(r)_{esc}^2 \rightarrow r_B \propto r^{5/3} \rightarrow q \sim 3$$