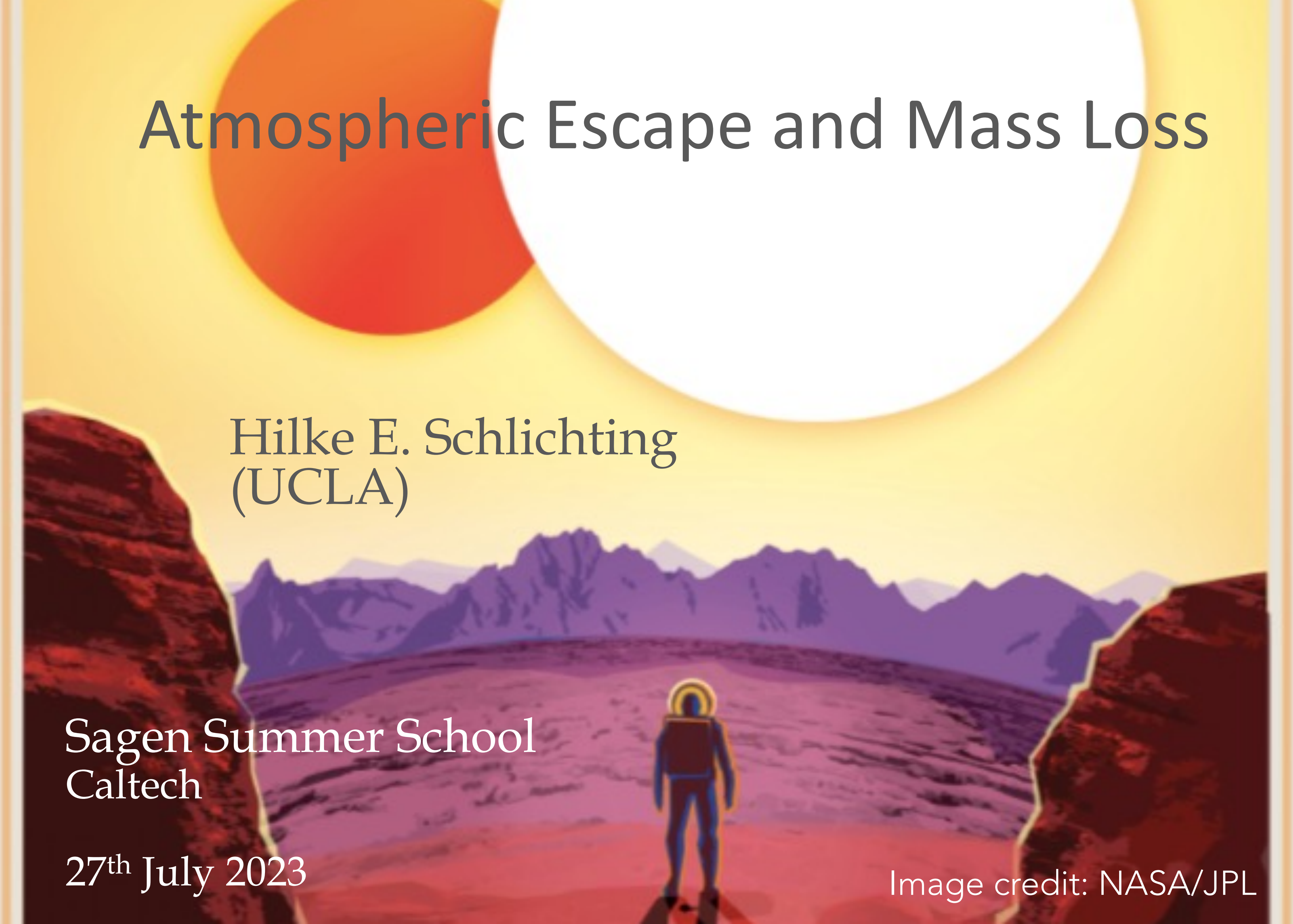
Atmospheric Escape and Mass Loss

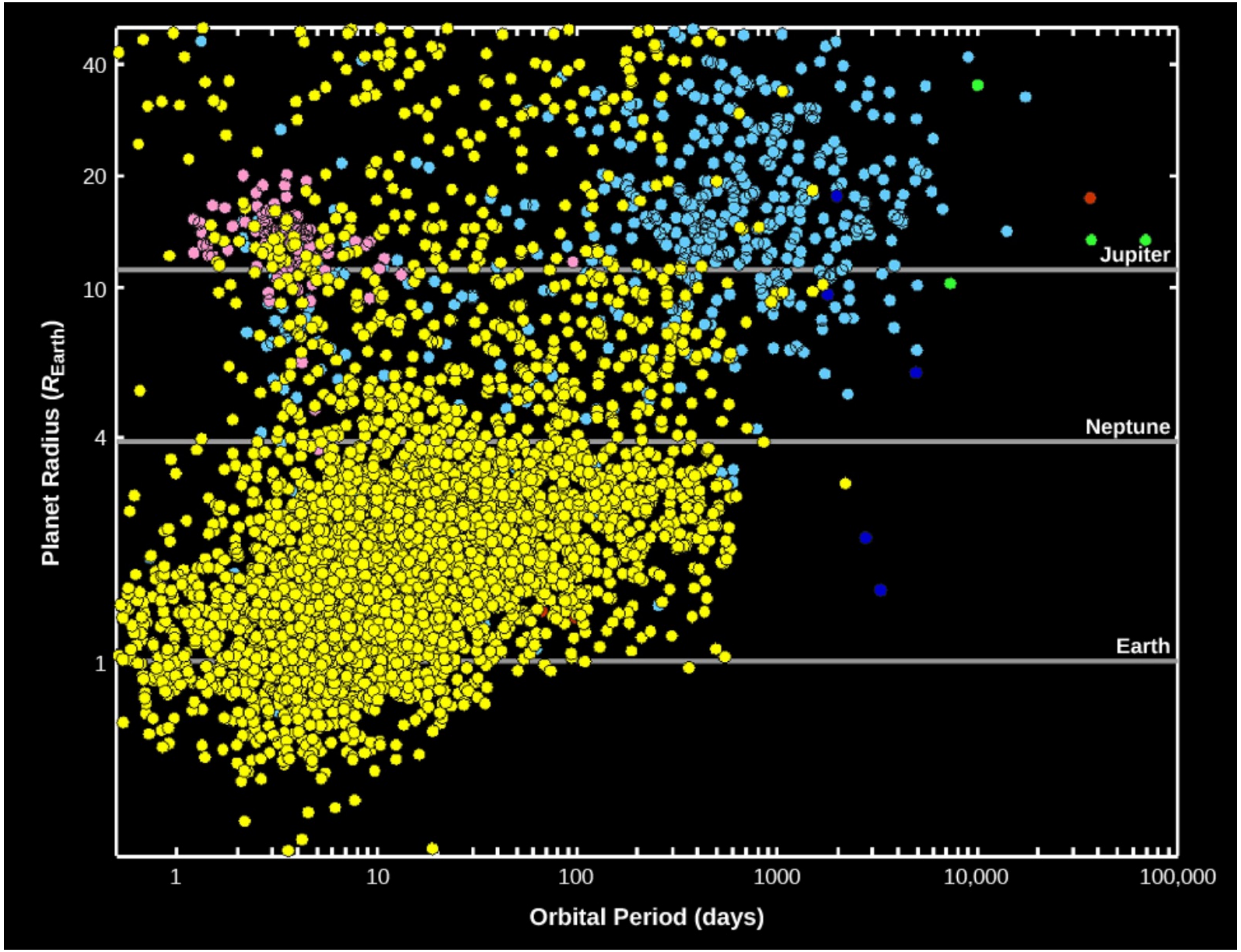


Hilke E. Schlichting
(UCLA)

Sagen Summer School
Caltech

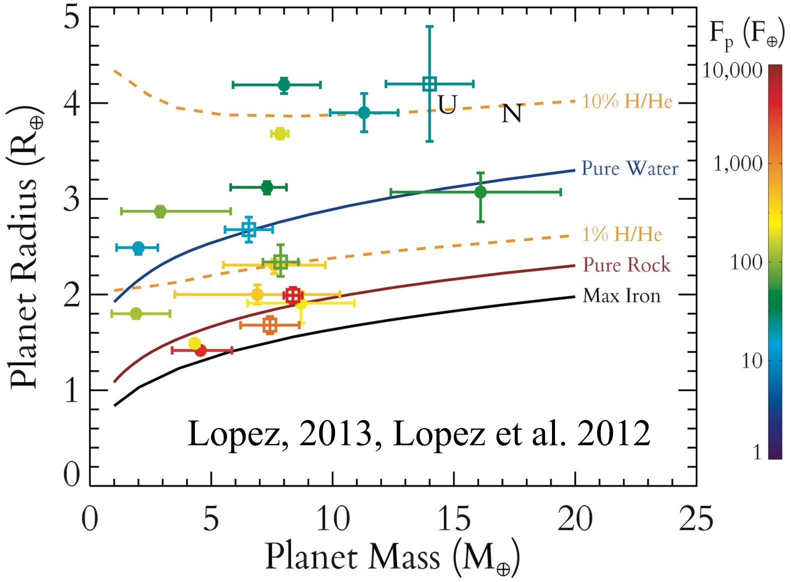
27th July 2023

Image credit: NASA/JPL

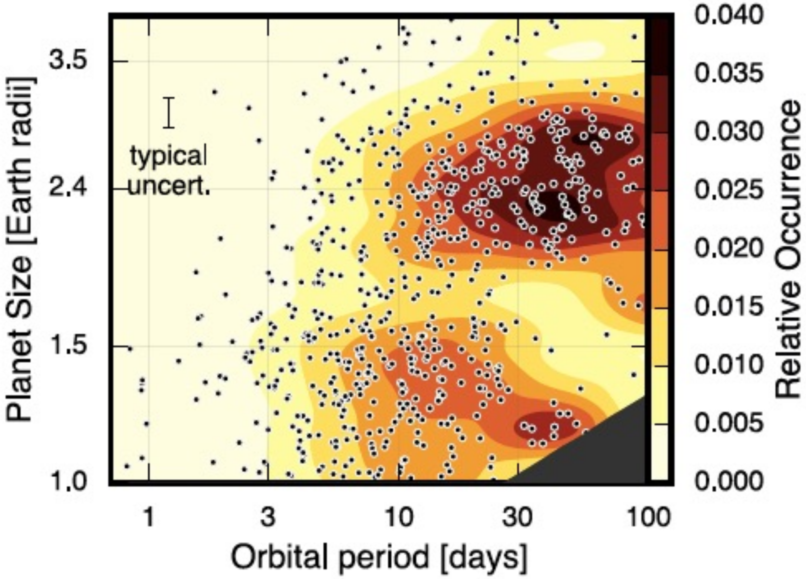


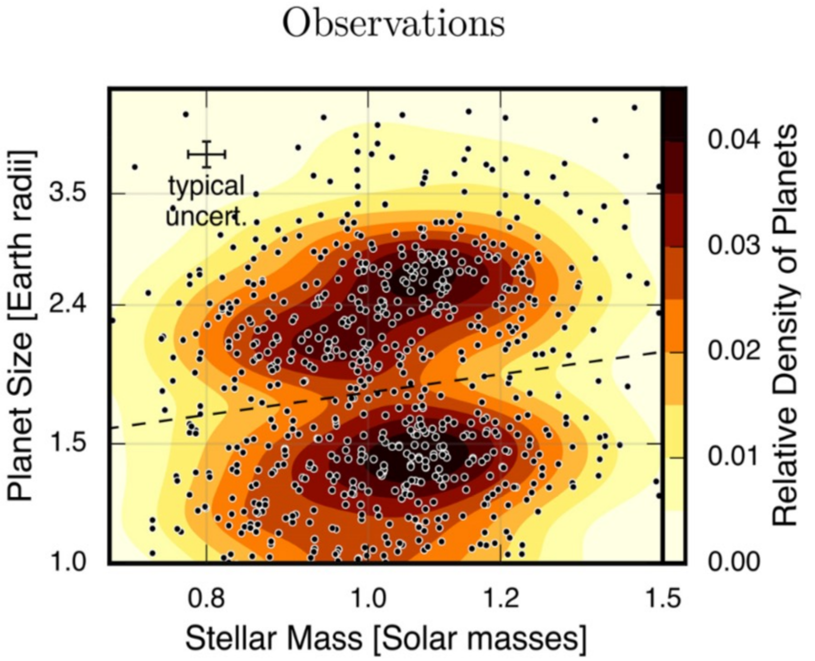
NASA/Exoplanet Archive

Super-Earths & Sub-Neptunes



Fulton & Pertigura 2018





Densities consistent with rocky composition for $R_p < 1.6$ R (e.g. Weiss et al. 2014, Rogers 2015)

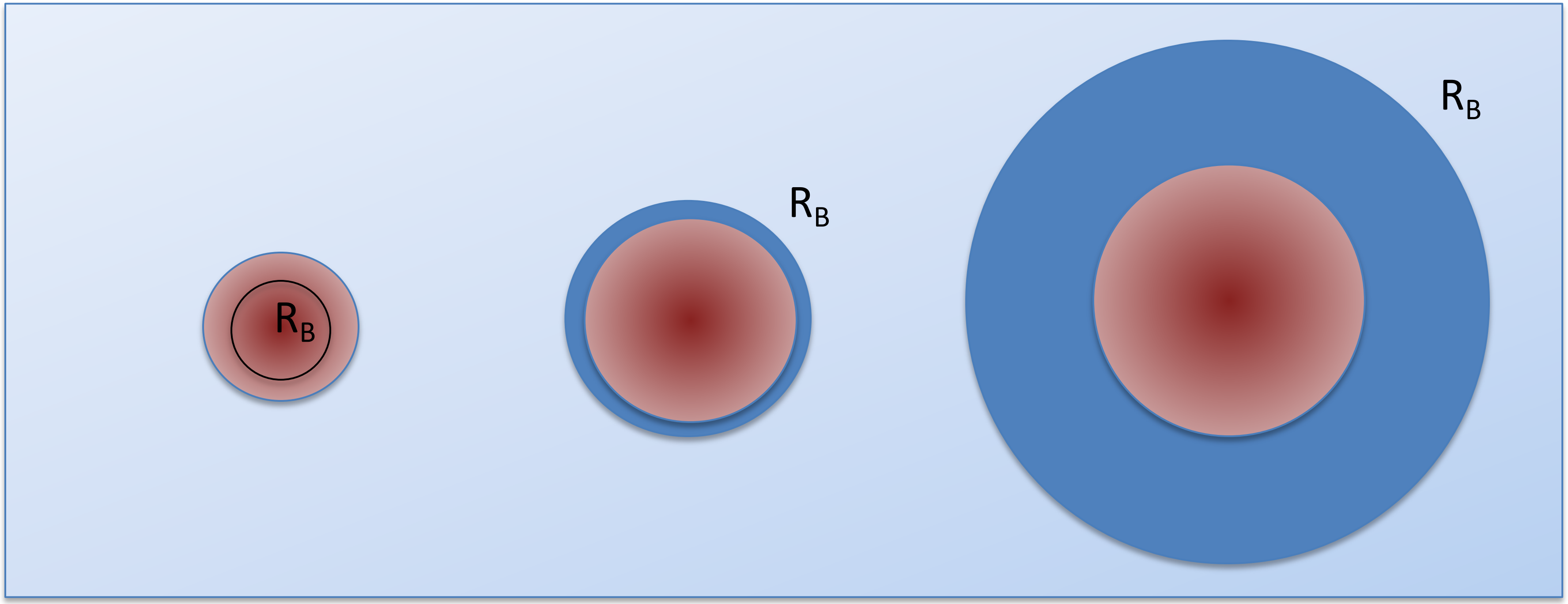
Slope: $\frac{\mathrm{d}\log R_p}{\mathrm{d}\log P} =$ -0.11 (Martinez et al. 2019)
-0.09 (Van Eylen et al. 2018)

Slope: $\frac{d \log R_P}{d \log M_*} \approx$ 0.26 (Berger et al. 2020)

Most abundant Planets in Galaxy know to date

(e.g. Fressin et al. 2013, Petigura et al. 2013)

Gas Accretion

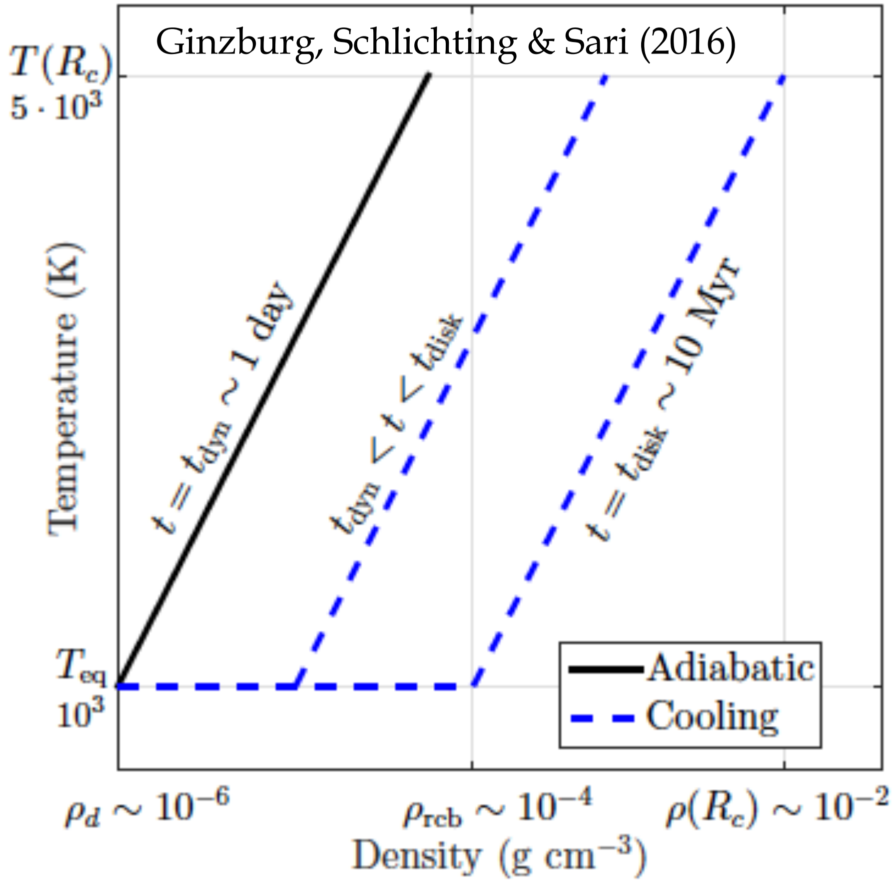


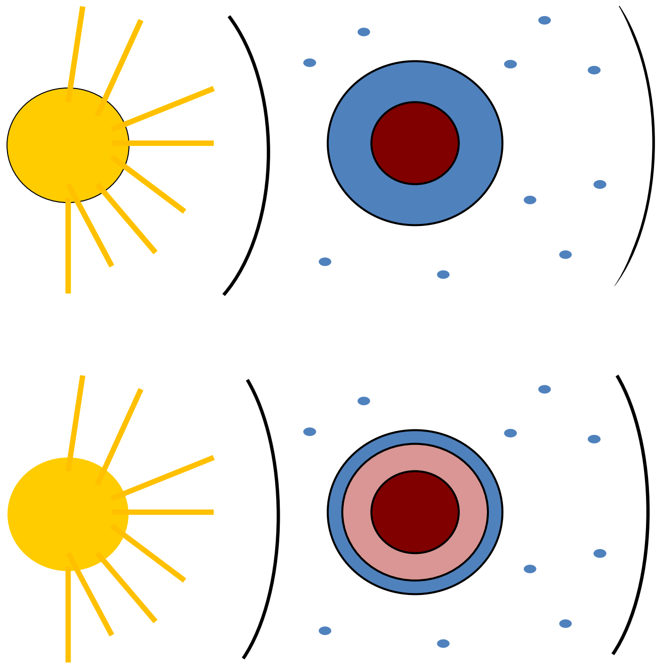
$R_B<R_P$ $R_B \sim R_P$ $R_B > R_P$

Bondi Radius $R_B \sim GM_p/c_s^2$

Core Temperature $T_c \sim GM_p\mu/k_BR_c \sim 10^4$-$10^5$K

Envelope Accretion:


Ginzburg, Schlichting & Sari (2016)



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

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

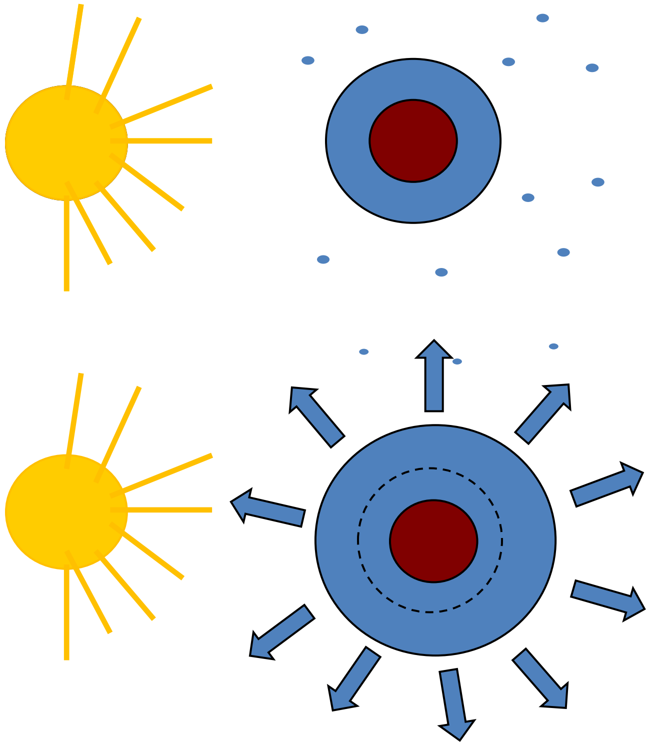
f only depends logarithmically on $\rho_{\rm disk}$

Spontaneous Evaporation/Boil-off due to Disk dispersal

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

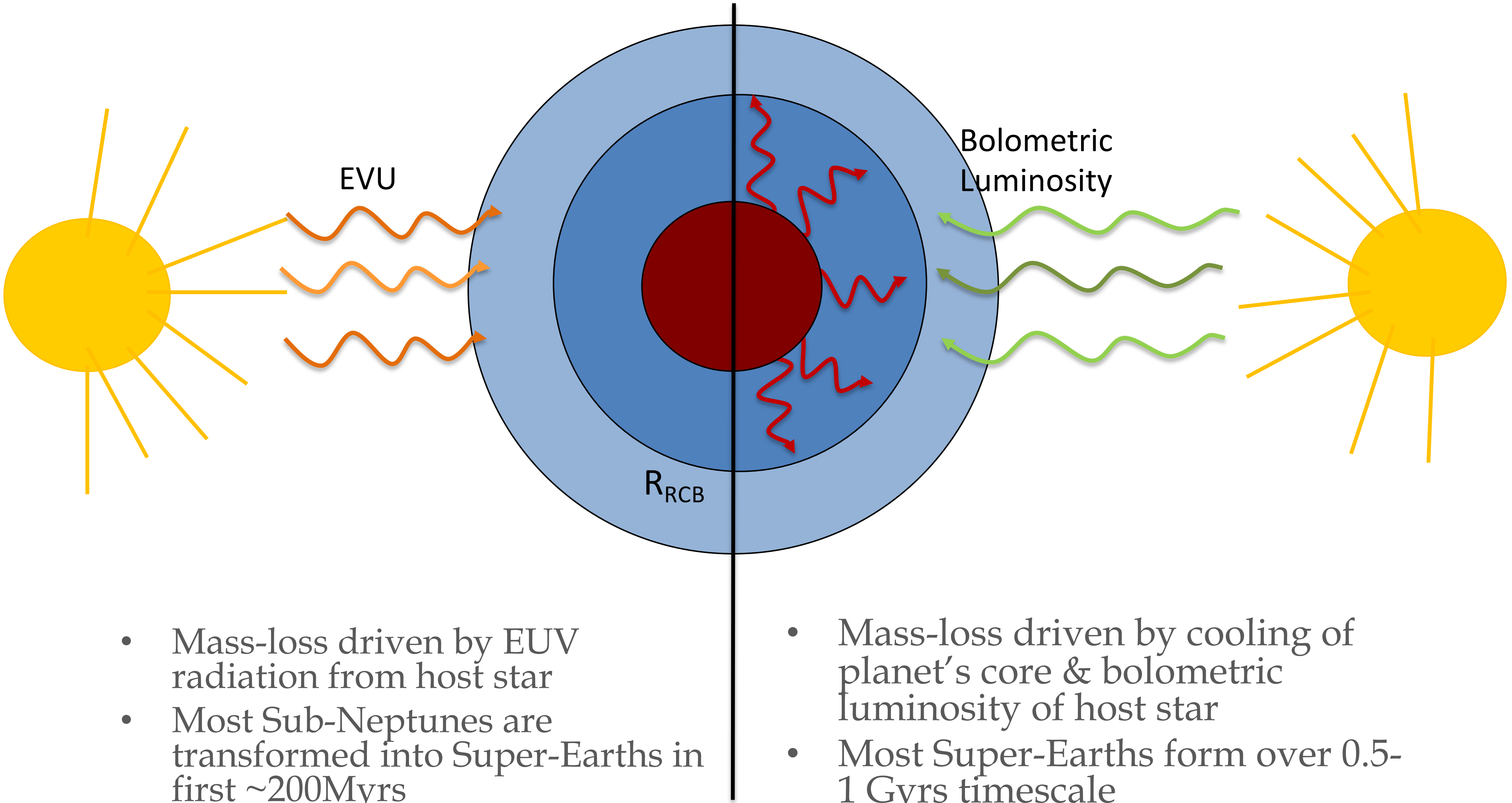
- Cooling of inner envelope can blow off the outer atmosphere
- Lose 25% (γ=1.2) to 70% (γ=7/5) of envelope mass
- $R_{\rm rcb}$ shrinks to ~ few R_c on t~ few $t_{\rm disk}$
- sets initial condition for thermal evolution models

$$f_{\rm semi-thin} \approx 0.01 \left(\frac{M_c}{M_\oplus}\right)^{0.44} \left(\frac{T_{\rm eq}}{10^3\ {\rm K}}\right)^{0.25} \left(\frac{t_{\rm disk}}{1\ {\rm Myr}}\right)^{0.5}.$$



e.g. Ikoma & Hori 2012, Owen & Wu 2016, Ginzburg, Schlichting & Sari 2016

Photo-evaporation VS Core-powered Mass-loss



- Mass-loss driven by EUV radiation from host star
- Most Sub-Neptunes are transformed into Super-Earths in first ~200Myrs

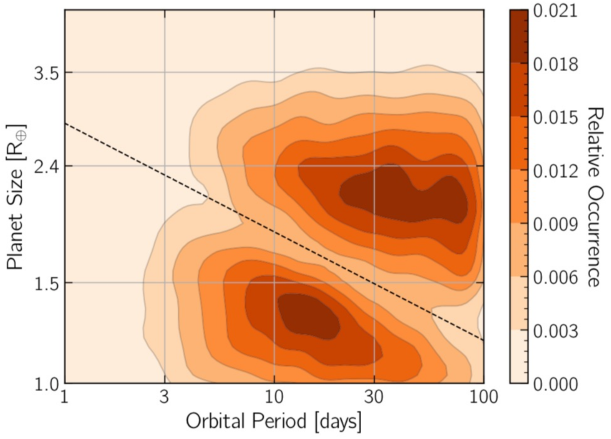
e.g. Owen & Wu (2014, 2017)

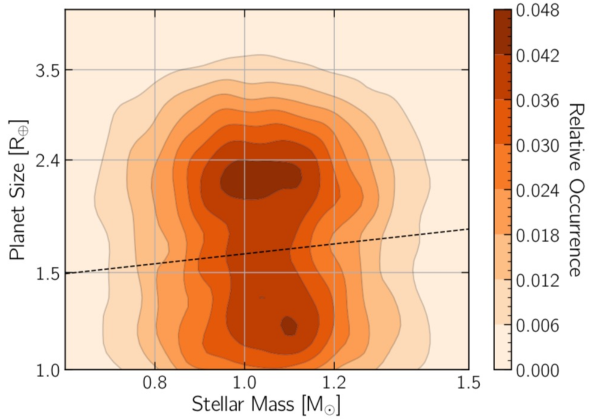
- Mass-loss driven by cooling of planet’s core & bolometric luminosity of host star
- Most Super-Earths form over 0.5-1 Gyrs timescale

e.g. Ginzburg et al. (2018), Gupta & Schlichting (2020)

Photo-Evaporation

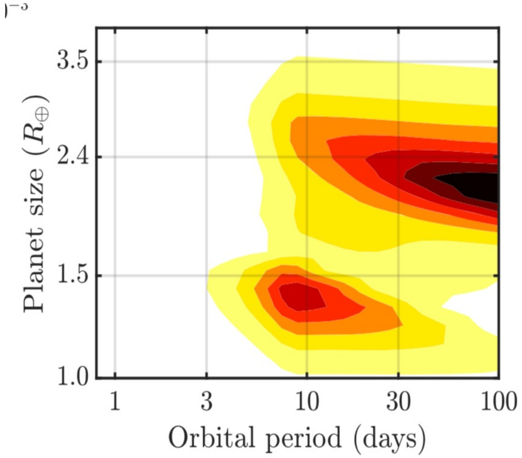
Rogers & Owen 2020



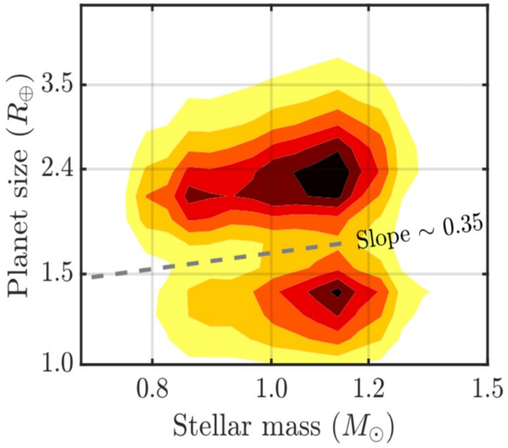


Core-powered Mass-loss

Gupta & Schlichting 2020

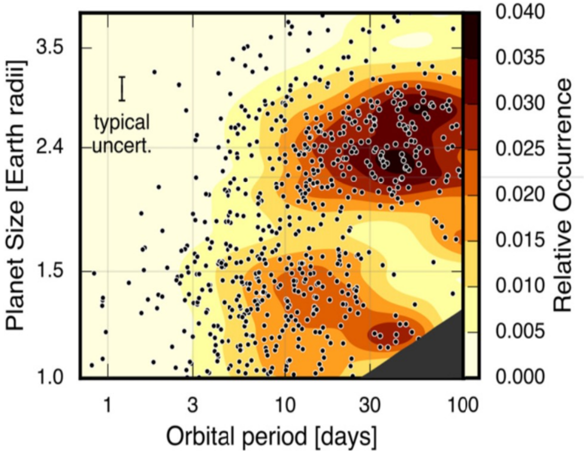


Model: CKS stellar distribution

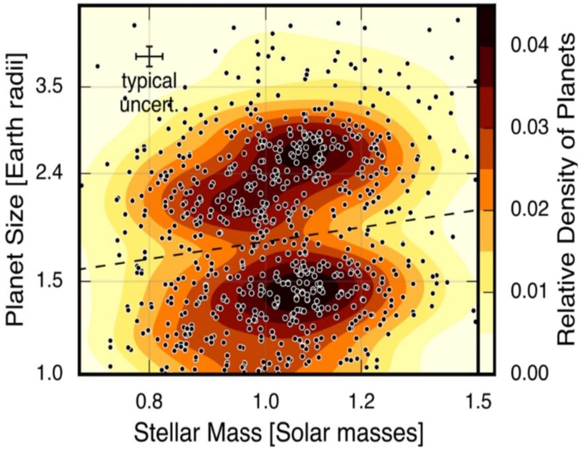


Observations

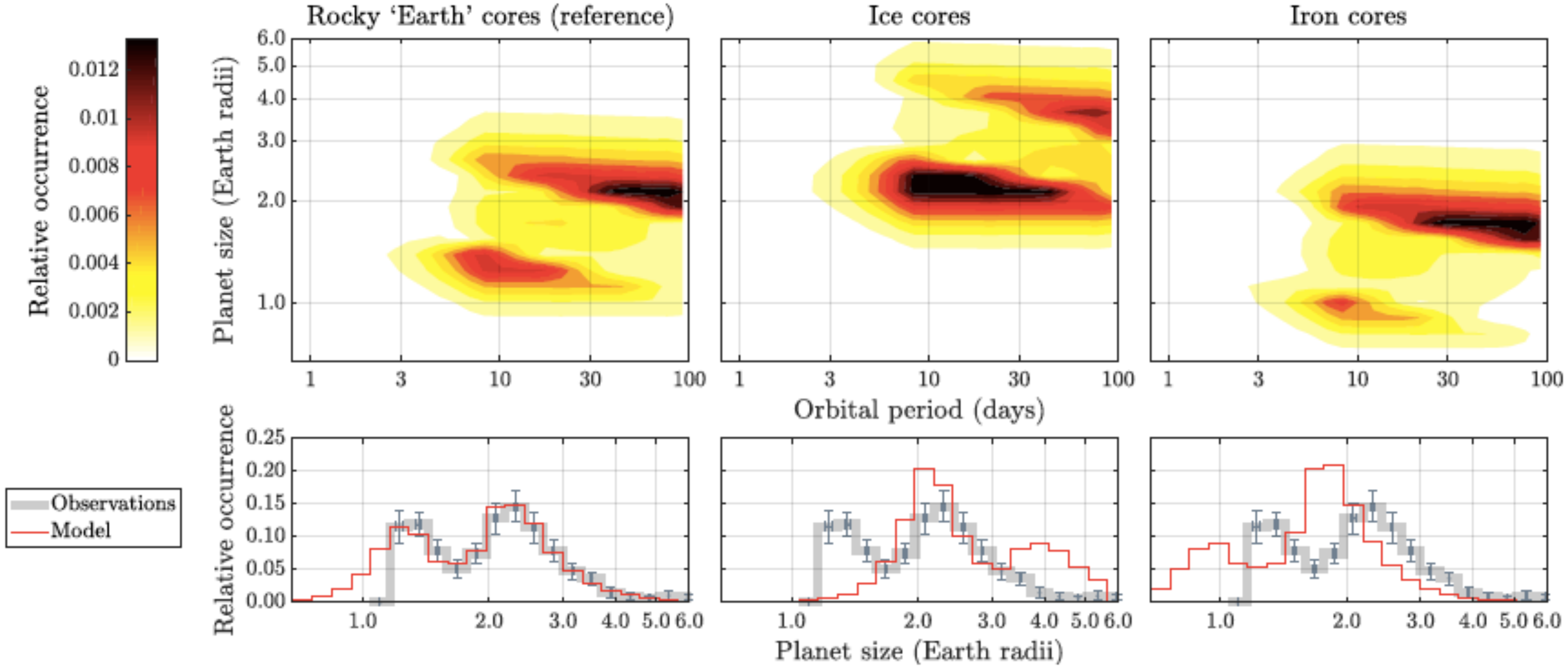
Fulton & Petigura 2018



Observations



Probing Core-Compositions

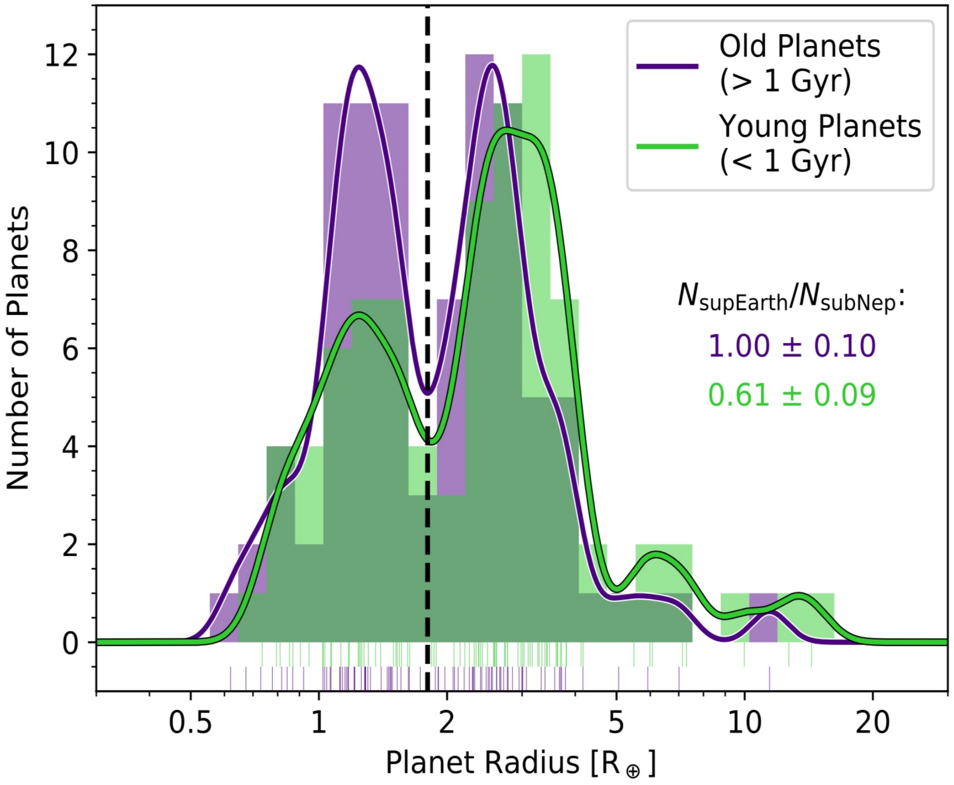


Gupta & Schlichting 2019

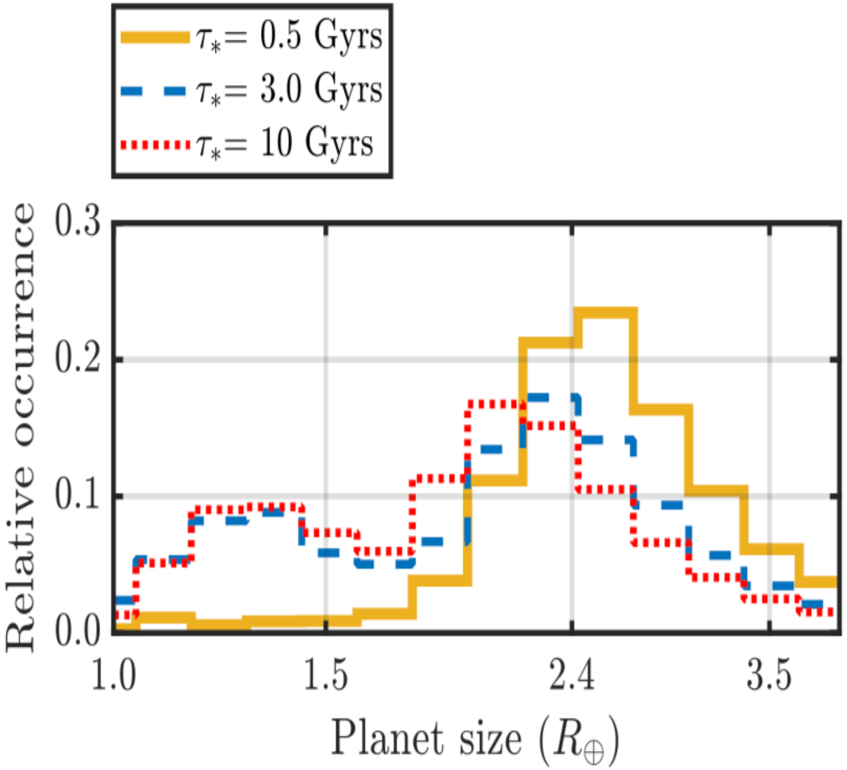
1) Location of valley is determined by core composition -> core-powered mass-loss & photoevaporation consistent with rocky 'earth'-like cores + most cores are water/ice poor ~ at most 20%

$t^B_{loss} \propto \exp(GM_p\ /(c_s^2 R_{rcb})) \propto \exp(R_p^3 P^{1/3} \rho_{c*}^{4/3})$ → Location of valley scales as $\rho_{c*}^{-4/9}$

Core-Powered Mass-loss Prediction:



Berger et al. 2020, see, e.g., also David et al. 2021



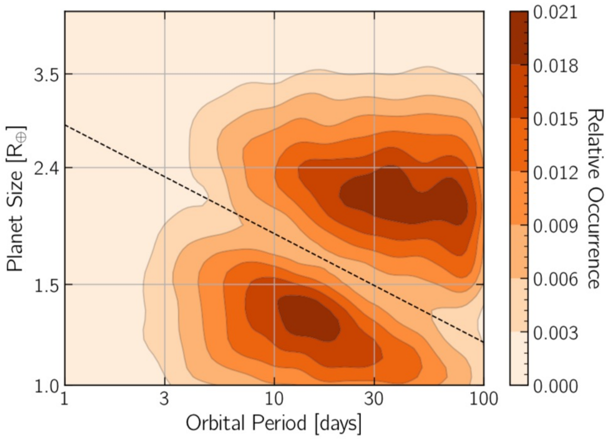
Gupta & Schlichting 2020

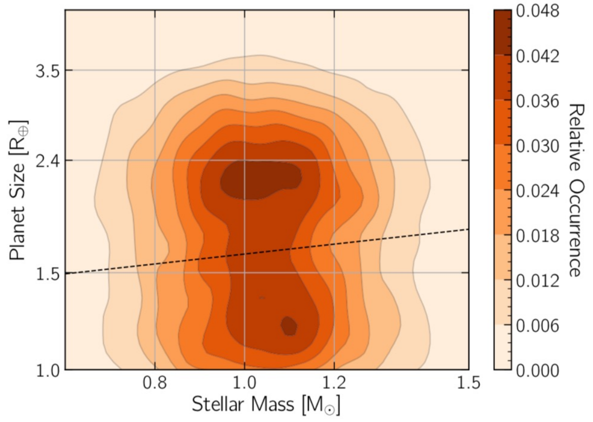
Most Super-Earths from over a 0.5-1 Gyrs timescale -> Can observe atmospheric mass-loss from Sub-Neptunes turning into Super-Earths today

Majority of Super-Earths formed with H/He envelopes & have bulk densities similar to Earth

Photo-Evaporation

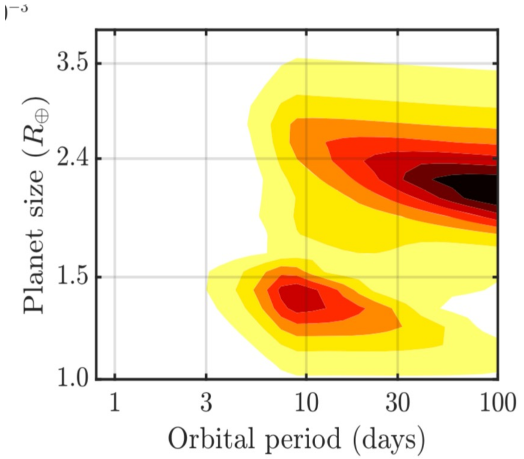
Rogers & Owen 2020





Core-powered Mass-loss

Gupta & Schlichting 2020



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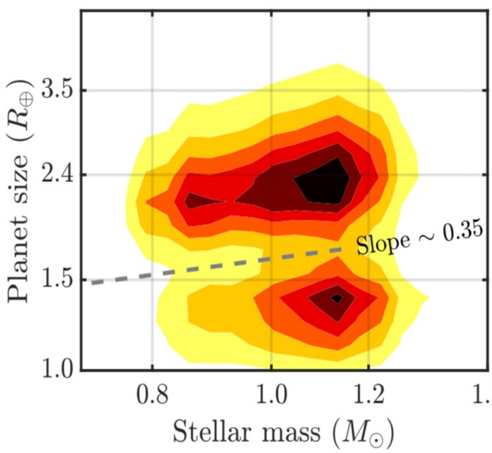
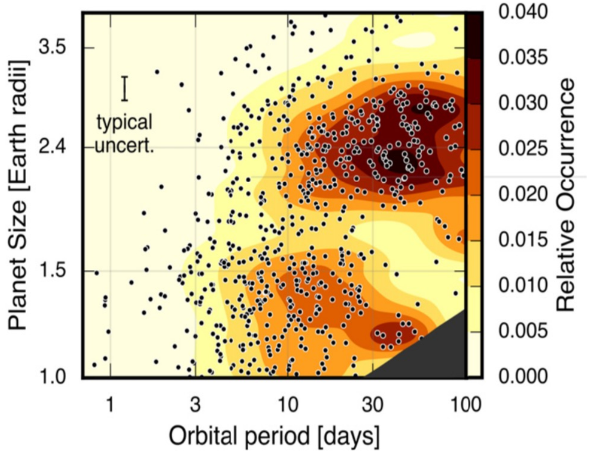


Observations

Fulton & Petigura 2018



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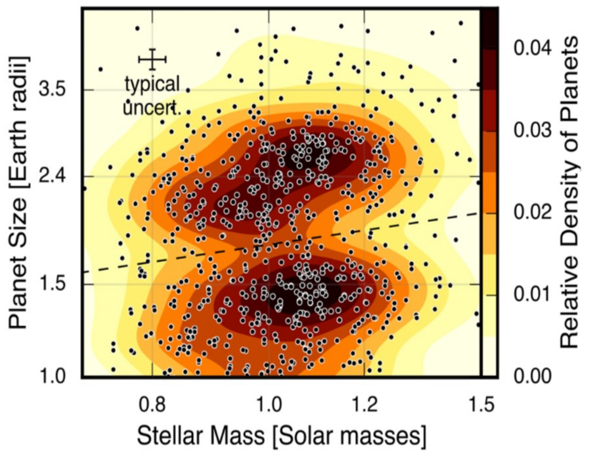
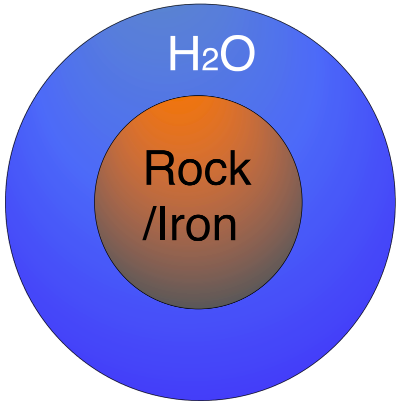
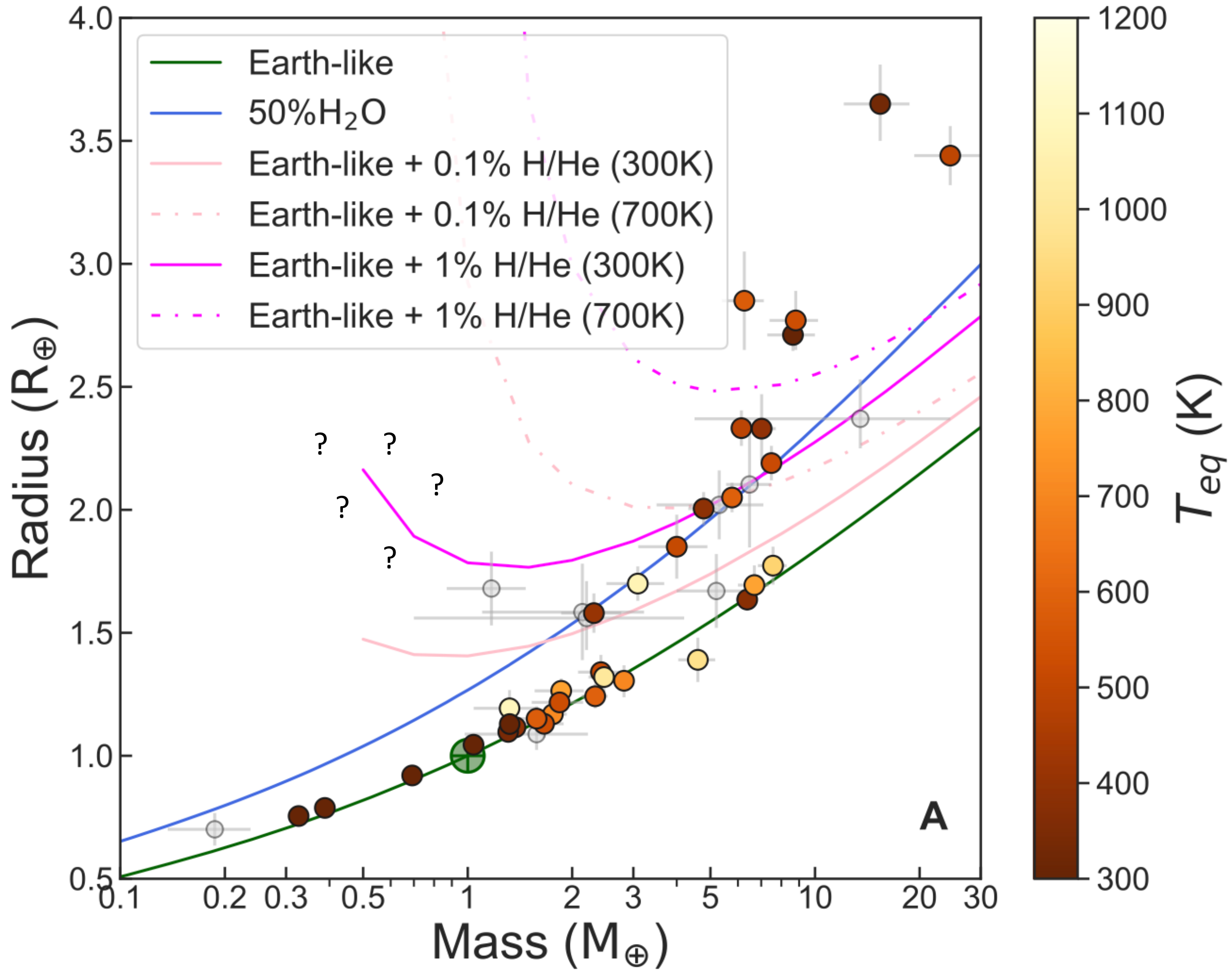


Signatures of atmospheric-mass loss on Mass-Radius relation

Water-World



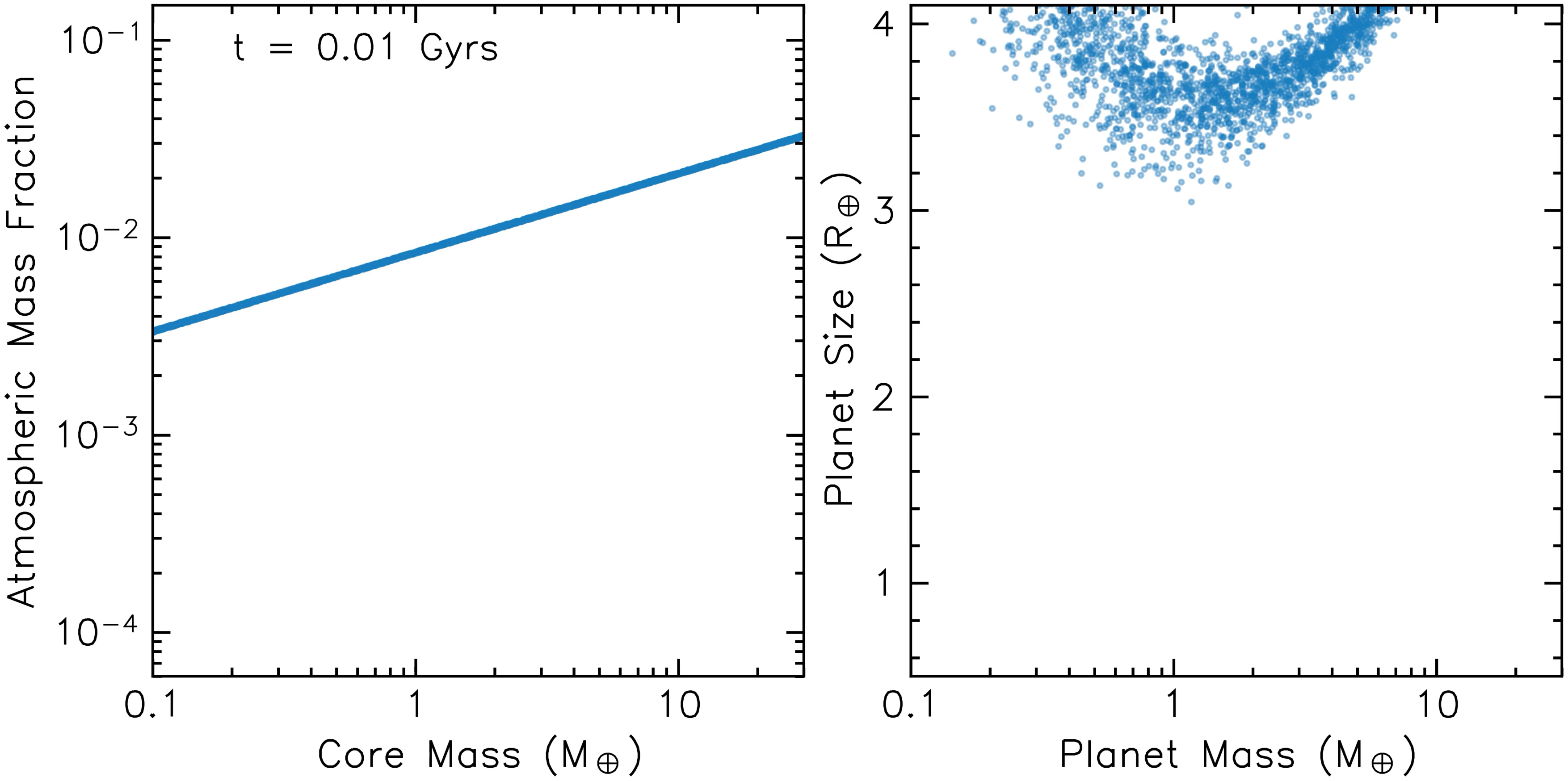
50%
water



Luque and Pallé (2022)

Constructing the correct mass-radius relations for H/He dominated atmospheres

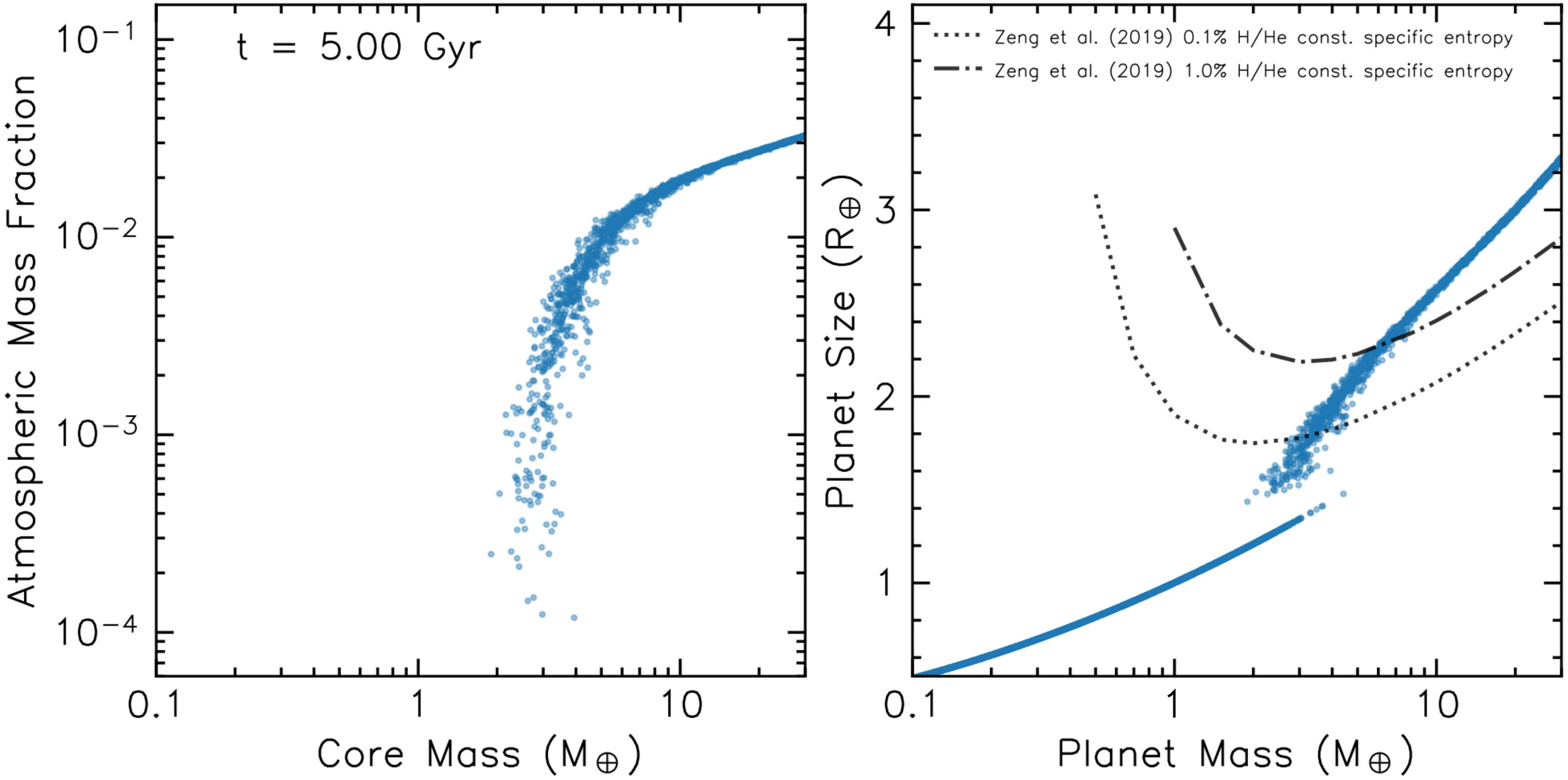
Planets at 500 K



Rogers, Schlichting and Owen (2023)

Constructing the correct mass-radius relations for H/He dominated atmospheres

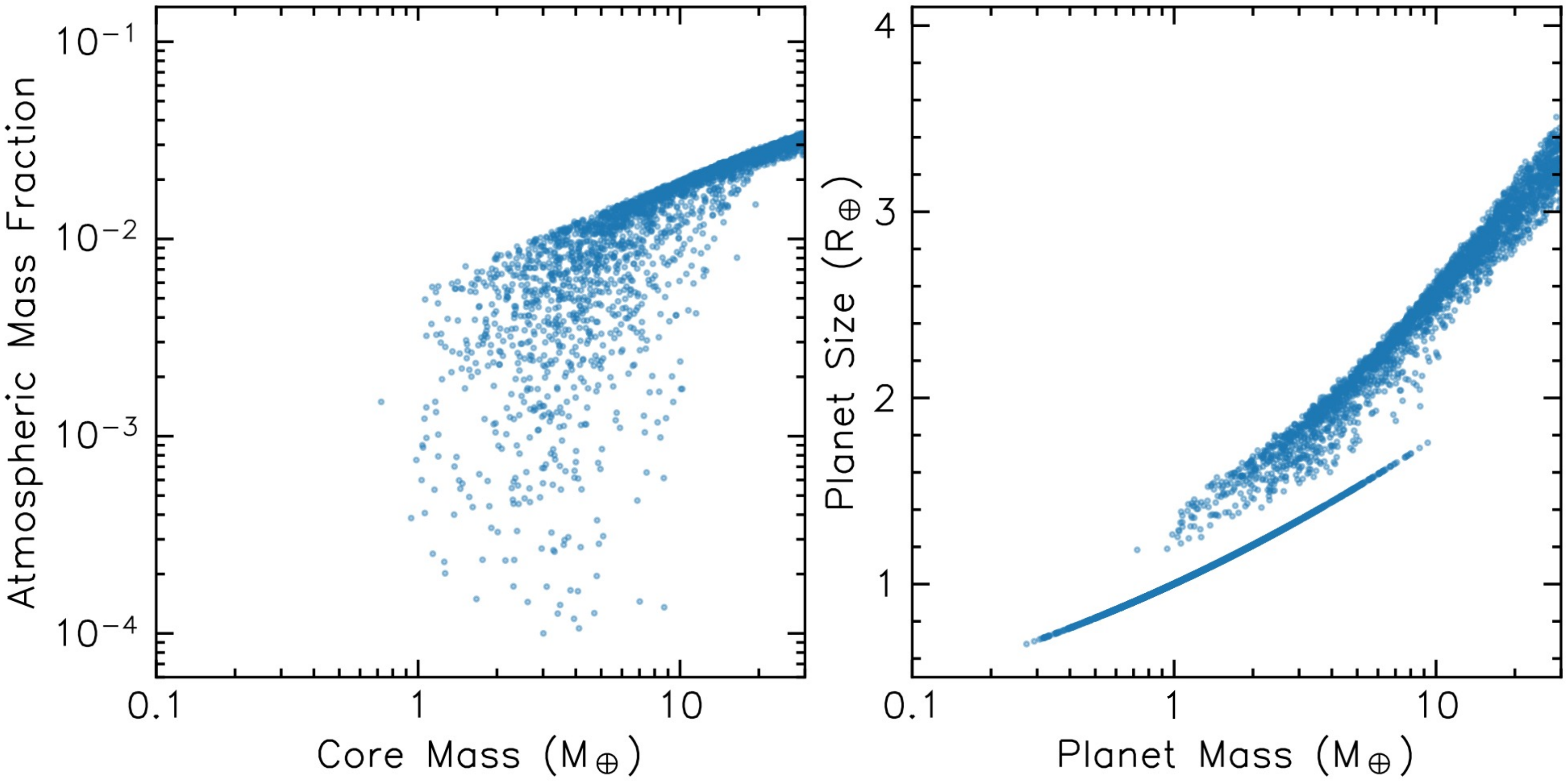
Planets at 500 K



Rogers, Schlichting and Owen (2023)

Constructing the correct mass-radius relations for H/He dominated atmospheres

Planets around M-dwarfs



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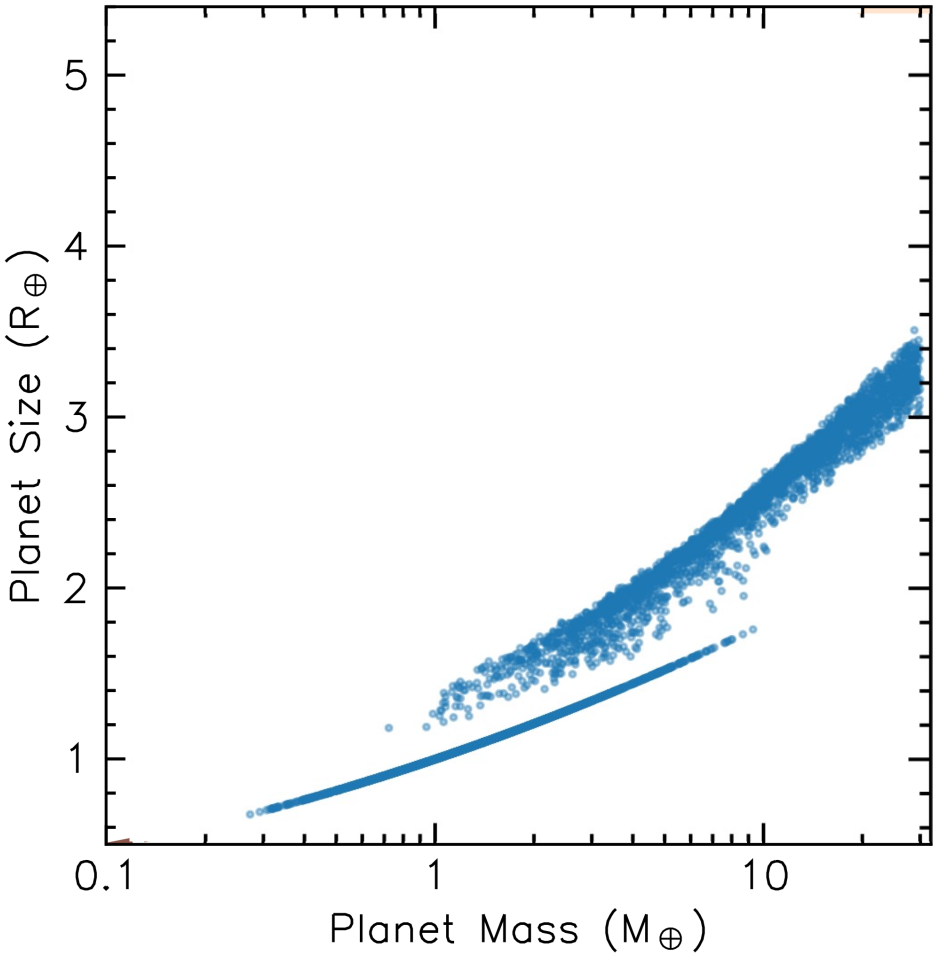


Rogers, Schlichting and Owen (2023)

Conclusions:

1) Atmospheric Mass-loss plays an active role in shaping the small exoplanet populations

2) Atmospheric Mass-loss needs to be accounted for when modeling the M-R relation of sub-Neptunes

3) Majority of Super-Earths formed with H/He envelopes & have bulk densities similar to Earth

Comparison with Observations

1) Core-powered mass-loss mechanism depends on the bolometric luminosity
2) Slope of the valley is set by $t_{loss} = t_{cool}$

$$t^B_{loss} \propto \exp(GM_p\ /(c_s^2 R_{rcb})) \propto \exp(R_p^3 P^{1/3} \rho_{c*}^{4/3})$$

$$\longrightarrow \quad \frac{\mathrm{d}\log R_p}{\mathrm{d}\log P} = -\frac{1}{9} \simeq -0.11$$

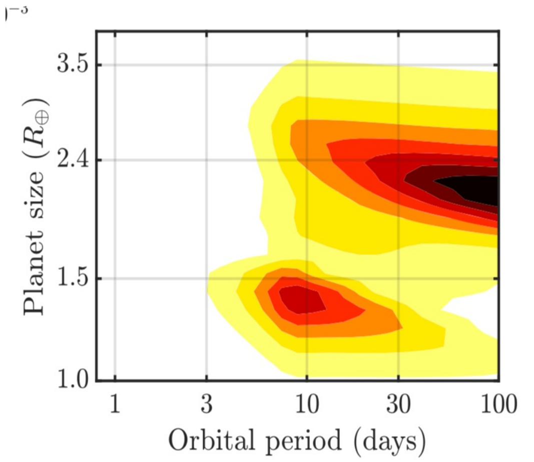
3) $t^B_{loss} \propto \exp(GM_p\ /(c_s^2 R_{rcb})) \propto \exp(R_p^3 T_{eq}^{-1})$

$$L_\star \propto M_\star^4$$

$$\longrightarrow \quad \frac{d\log R_P}{d\log M_*} = 0.28$$

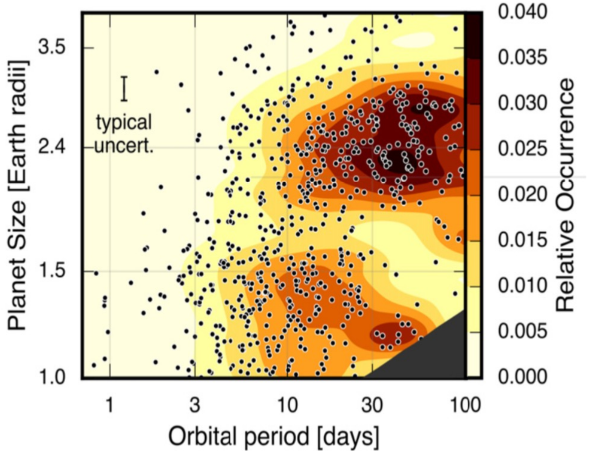
Core-powered Mass-loss

Gupta & Schlichting 2020



Observations

Fulton & Petigura 2018



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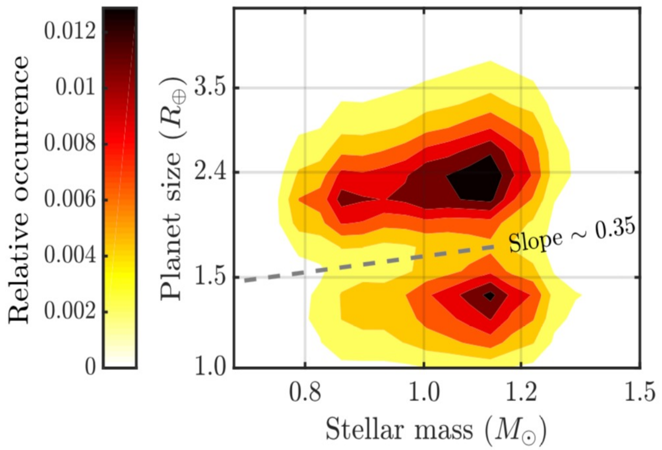

Observations