The Origin of Radius Valley

Xiaoyi Ma, Yu Wang, Xiao Li, Zhaoning Liu

Advisor: Wei Zhu

Student Seminar
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Outline

- Background: Observational discovery of radius valley
- Theoretical models: photoevaporation, core-powered
- Observational evidences of two models
- Other models for radius valley

Background

Observational Discovery of Radius Valley

Xiaoyi Ma
马潇依

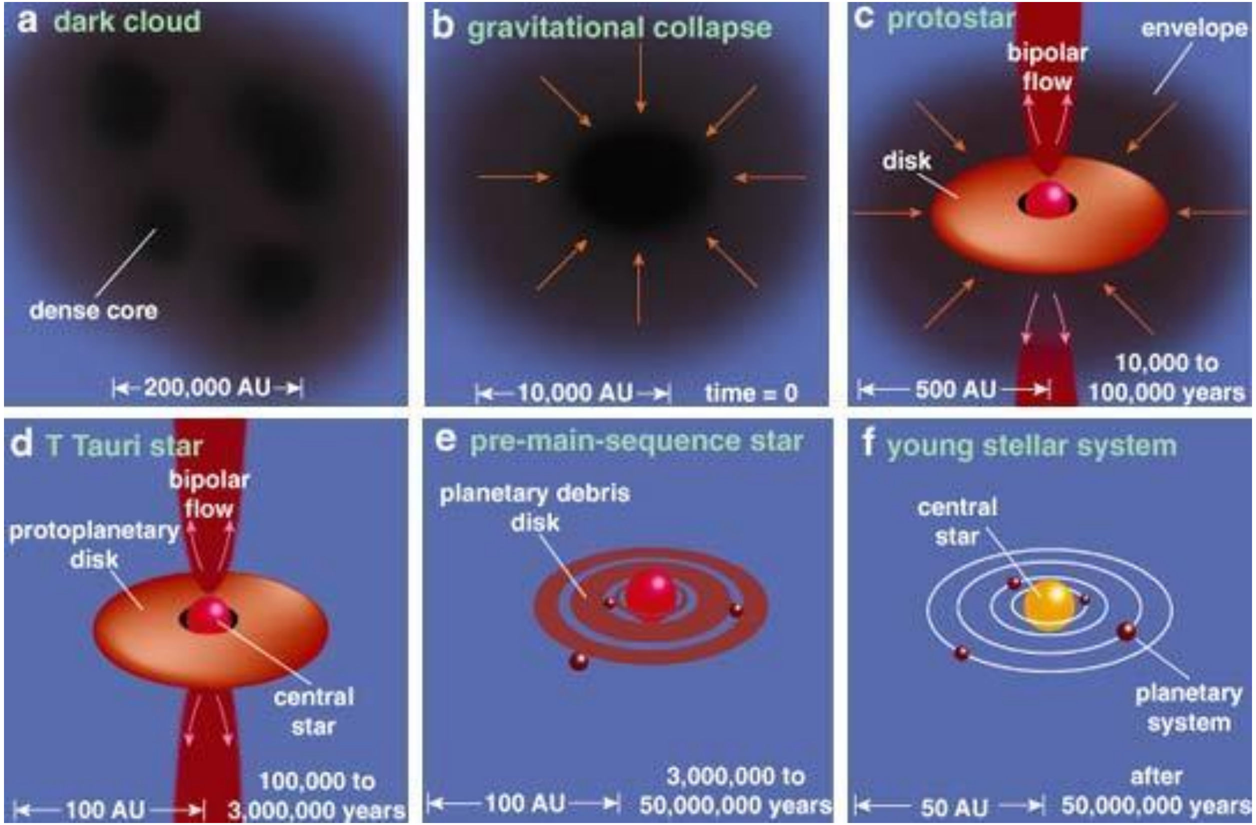
Outline

- Planetary system formation
- Kepler mission
- What is radius valley?
- Keys of its discovery:
- Theoretical prediction
- Observational discovery
- Relation with stellar mass and orbital period

Take-home message

The **radius valley** is a region of low occurrence rate for **close-in** exoplanets at **planet radii ~ 2 $R_\oplus$**, which its position is decreasing with orbital period and increasing with stellar mass.

How does planetary system form?



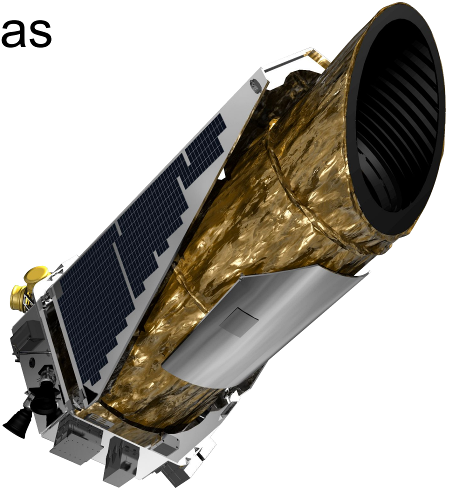
Cartoon from Greene, American Scientist (2001)

Kepler Mission

- NASA *Kepler* mission is launched in 2009 to discover **exoplanets**, which leads many remarkable discoveries of planetary systems.

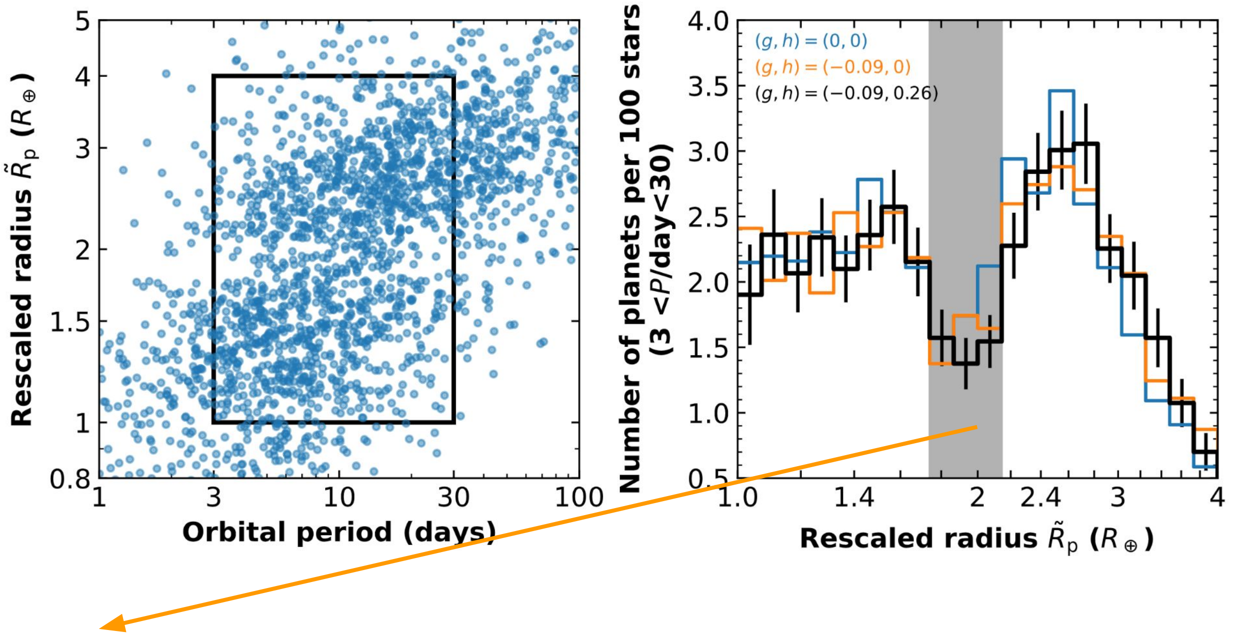
- ***Kepler* photometry** enabled the detections of the planets as the small as Mercury and **confirmed the prevalence of planets smaller than Neptune**.

- **California-Kepler Survey (CKS)** is spectroscopic survey to measure the properties of *Kepler* planets and their host stars. Its motivation is to **reduce the uncertainty in the size of *Kepler* planet and star**.



Petigura et al. (2017)

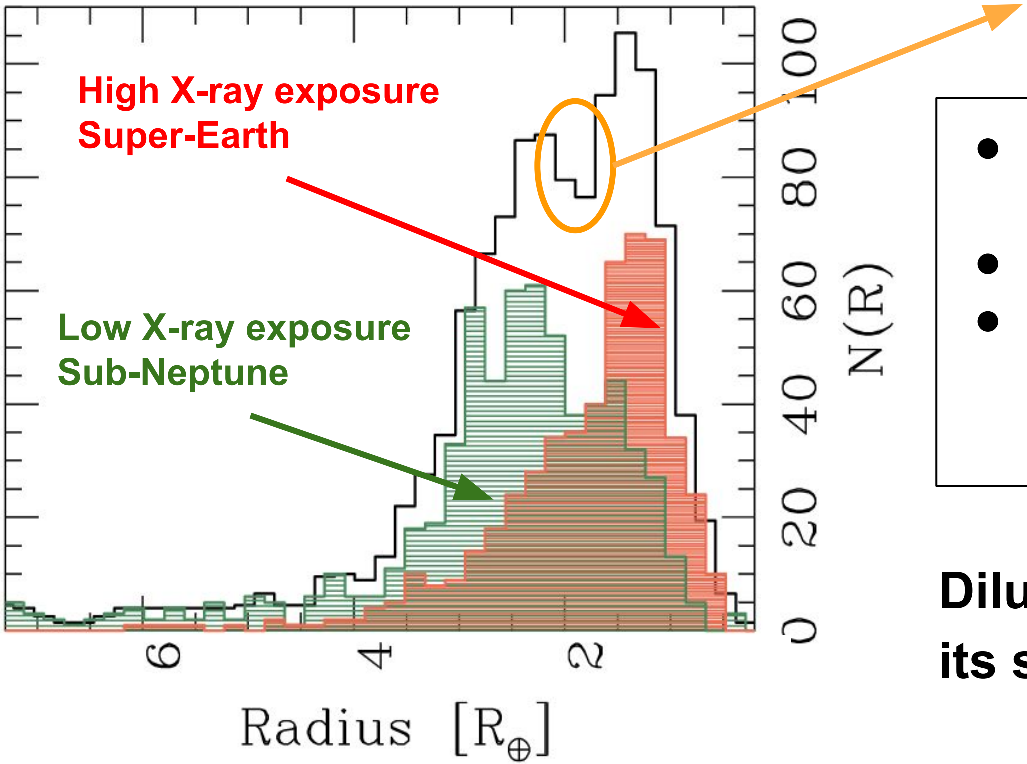
What is radius valley?



The **radius valley** is a region of low occurrence rate for **close-in** exoplanets at **planet radii ~ 2 $R_\oplus$**

Zhu & Dong (2021)

Theoretical Prediction



High X-ray exposure
Super-Earth

Low X-ray exposure
Sub-Neptune

Radius valley?

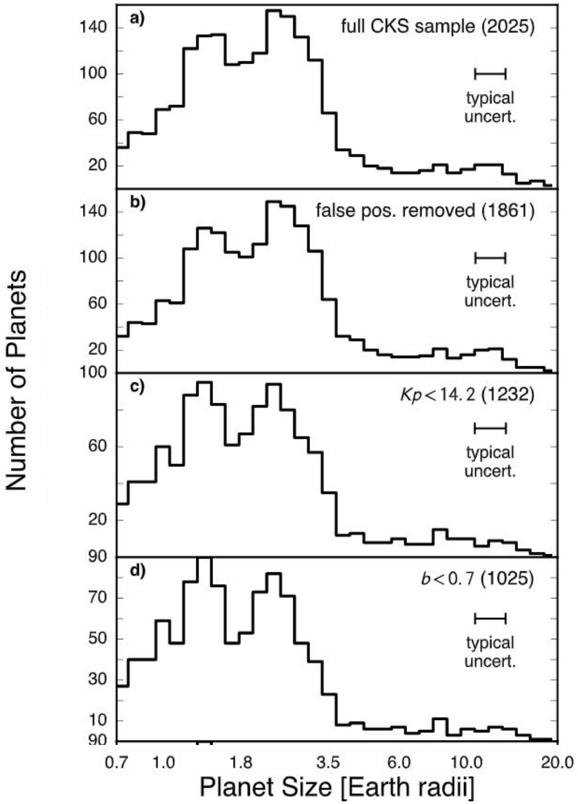
- Large planet radius uncertainty
- Potential false positives
- Not consider detection efficiency bias (completeness correction)

Diluted the gap and reduced its statistical significance.

Owen and Wu (2013)

CKS spectroscopy --- Sampling

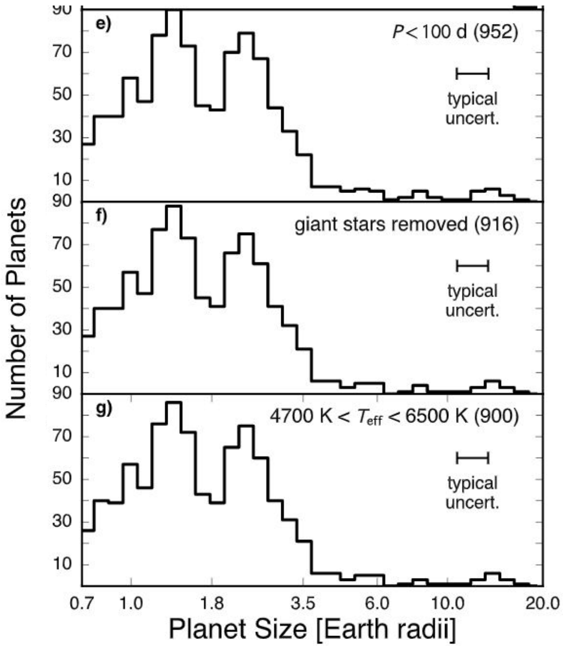
With the stellar sample from CKS spectroscopy, they achieved the median uncertainties in planet radii of 12%



Remove false positive

Remove faint stars

Remove high impact parameter stars



Remove Long-period stars

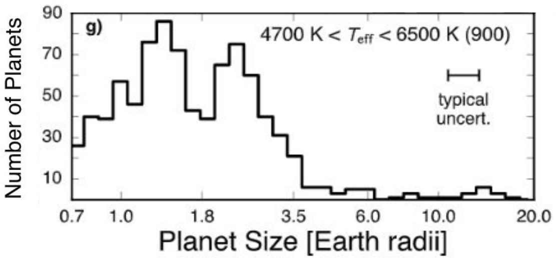
Remove giant stars

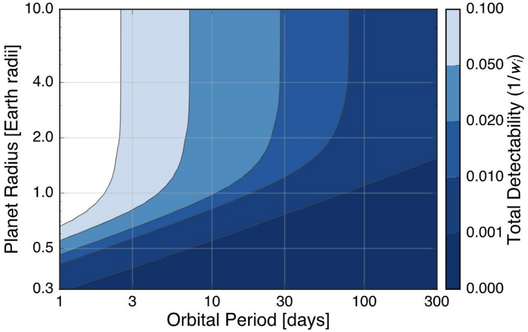
Restricted into high spectral resolution temperature range

Fulton et al (2017)

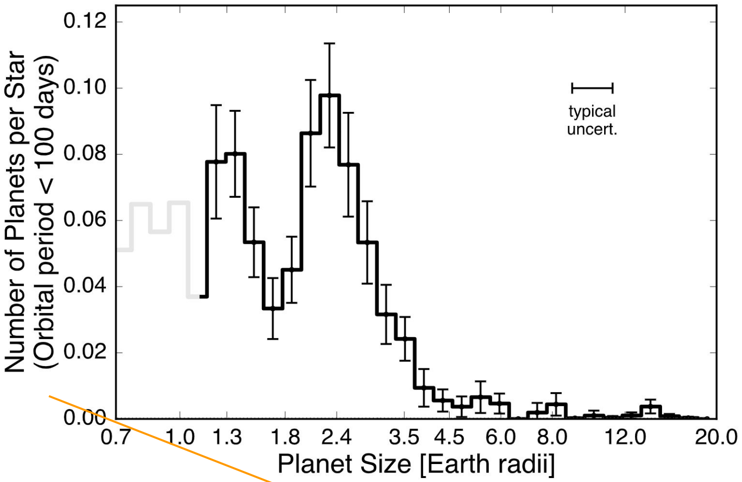
CKS spectroscopy --- Completeness Correction

Filtered Distribution





Final Distribution
(occurrence rate)



Completeness Correction

$$w_i = \frac{1}{(p_{\rm det} \cdot p_{\rm tr})}$$

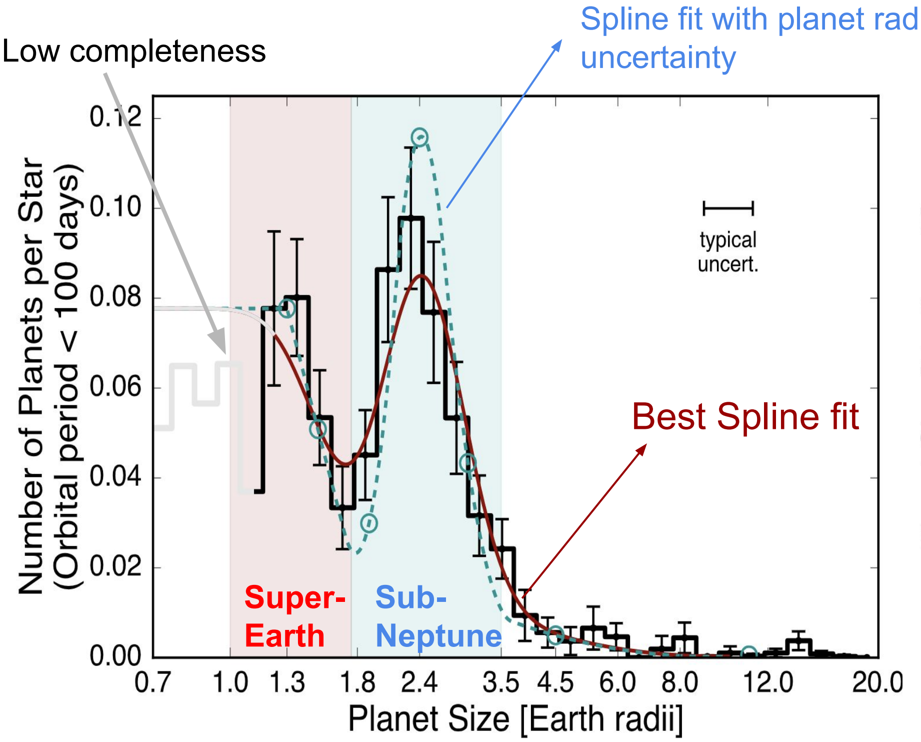
Pipeline completeness
(Detection probability)

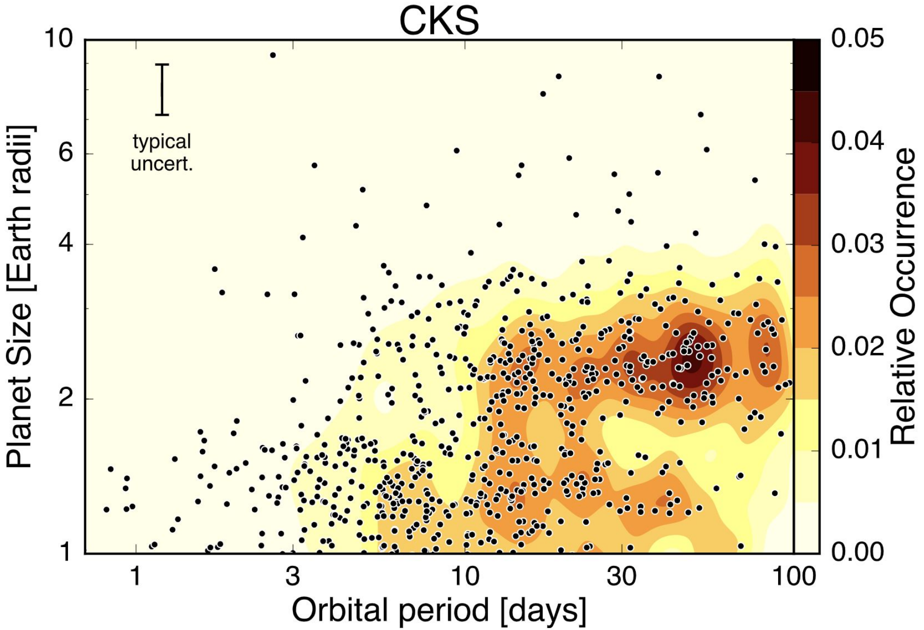
Transit probability

$$f_{\rm bin} = \frac{1}{N_\star} \sum_{i=1}^{n_{\rm pl,bin}} w_i$$

Fulton et al (2017)

CKS spectroscopy --- Radius gap

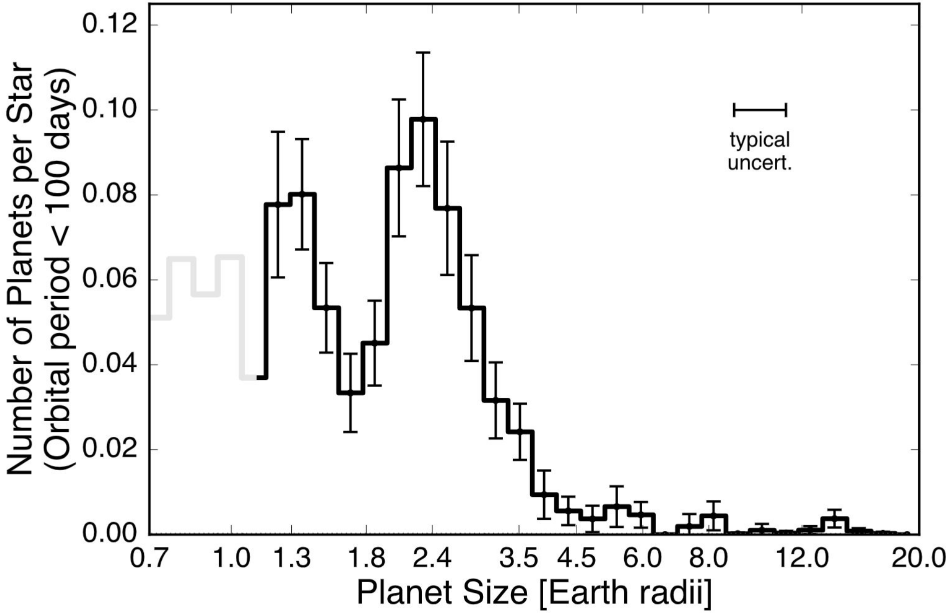


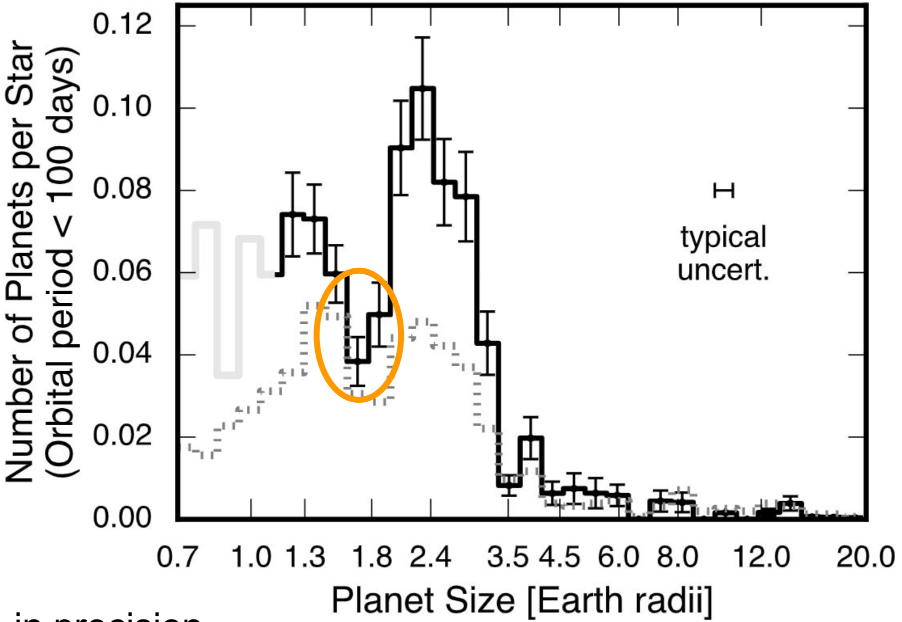


Bimodal distribution of super-Earth (~1.3R⊕) and sub-Neptune (~2.4R⊕) and a **deficit in occurrence rate at 1.5-2.0 R⊕**, which is the **radius gap**.

Fulton et al (2017)

Gaia DR2 parallaxes --- Radius valley





Without *Gaia* Data
(12%)
(Fulton 2017)

Increase in precision
Unchanged distribution

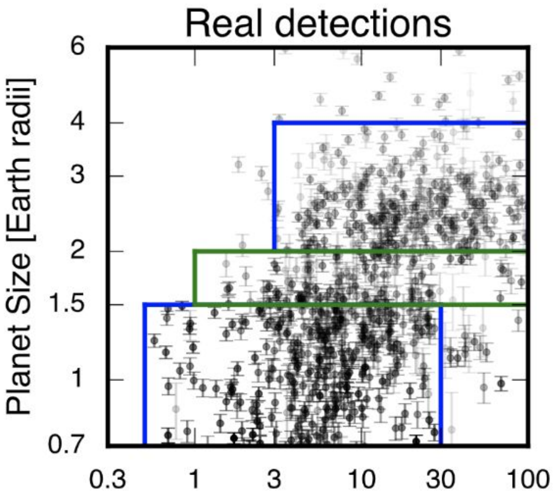
Resolved intrinsic spread of super-Earth and sub-Neptune

With *Gaia* Data
(5%)
(Fulton 2018)

Fulton & Petigura (2018)

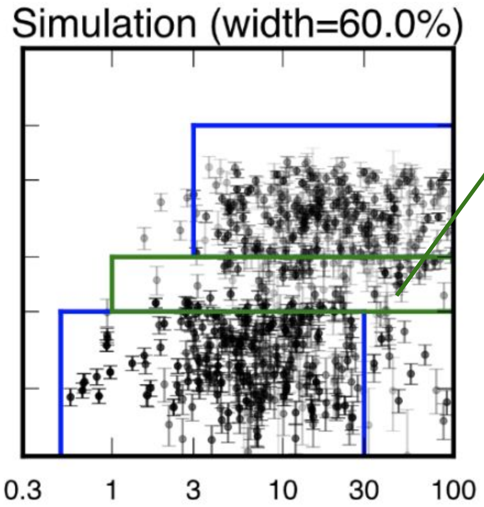
Gap or Valley?

Planets reside between 1.5-2.0$R_\oplus$ are due to **measurement uncertainty alone (gap)** or **intrinsic spread of super-Earth and sub-Neptune (valley)?**



Assign new radius according to uniform distribution

for super-Earth or sub-Neptune



The planets reside in the region is due to **intrinsic spread** of super-Earth and sub-Neptune.

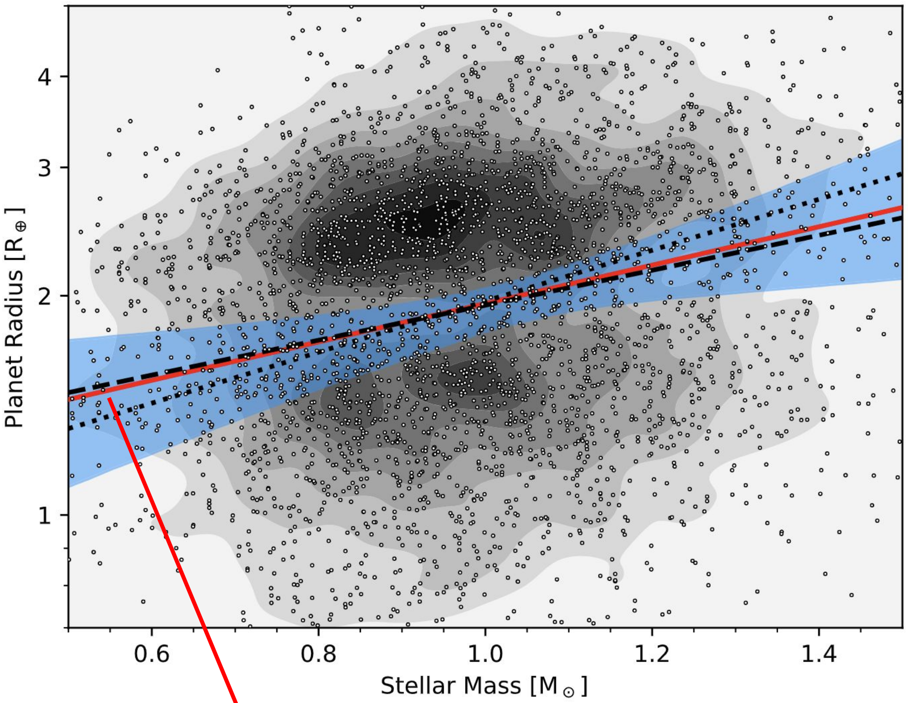
Radius valley

Fulton & Petigura (2018)

Stellar mass and period relation

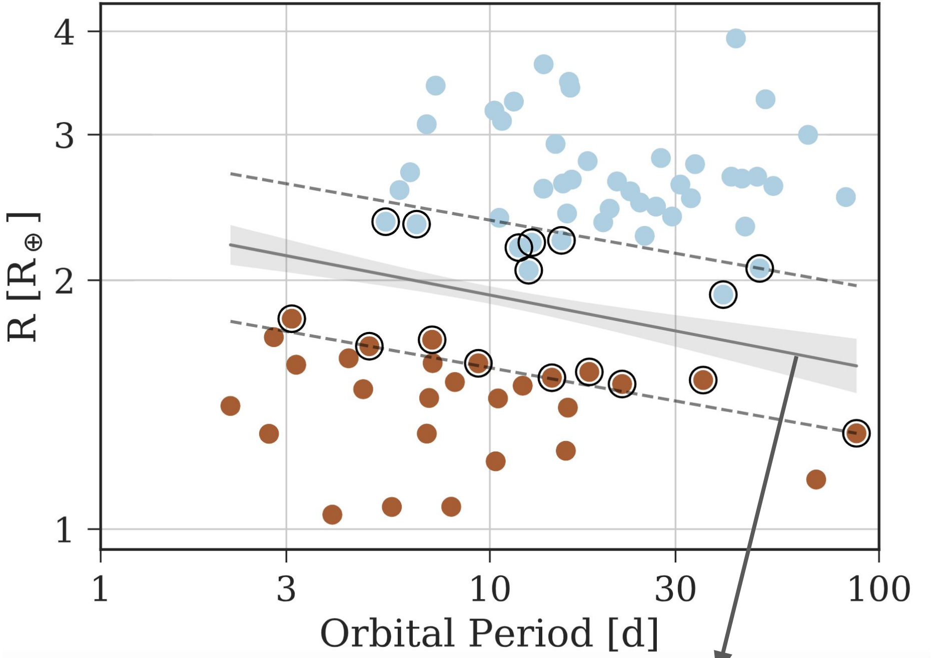
$$\frac{R_{\mathrm{p}}}{R_{\mathrm{p}}^{\mathrm{valley}}} = \left(\frac{P}{10\,\mathrm{days}}\right)^{g} \left(\frac{M_\star}{M_\odot}\right)^{h}$$

Zhu & Dong (2021)



$$h = 0.26^{+0.21}_{-0.16}$$

Berger et al. (2020)



$$g = -0.09^{+0.02}_{-0.04}$$

Van Eylen et al. (2018)

Fulton & Petigura (2018)

Backup 2 --- How to derive stellar radius?

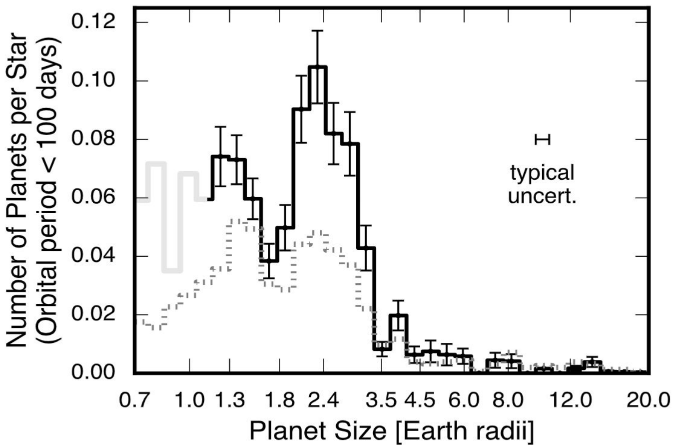
The stellar radius derived from the Stefan-Boltzmann law:

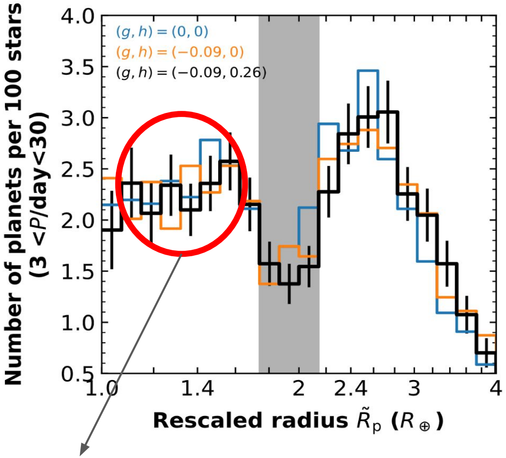
$$R_\star = \left(\frac{L_0 10^{-0.4 M_\mathrm{bol}}}{4\pi\sigma_\mathrm{sb} T_\mathrm{eff}^4} \right)^{1/2} \qquad M_\mathrm{bol} = m - A - \mu + BC$$

Therefore, the stellar radius is determined by:

● Apparent magnitude m	***Kepler* photometry**
● Effective temperature T_eff	**CKS spectroscopy**
● Line-of-sight extinction A	3D dust map (Green et al. 2018)
● Distance modulus μ	***Gaia* DR2 parallax**
● Bolometric correction BC	Isoclassify package (Huber et al. 2017)

Backup 3 --- Problem of IDEM approach





Why there is no single sharp peak?

Possible reason: The IDEM approach Fulton (2017,2018) used to calculated the number of planets per star tends to underestimate the occurrence rate for small planets due to its low sensitivity (survey detection efficiency).

Inverse detectivity efficiency method
(used by Fulton)

$$\bar{n}_p^{\mathrm{IDEM}} = \frac{1}{N_\star}\sum_{i=1}^{N_p}\frac{1}{\boxed{p_i}} = \frac{N_p}{N_\star}\left\langle \frac{1}{p} \right\rangle$$

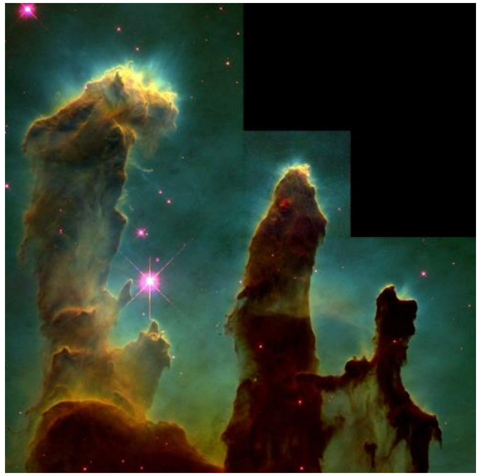
Maximum likelihood
(used by Zhu)

$$\bar{n}_p^{\mathrm{ML}} = \frac{N_p}{\sum_{j=1}^{N_\star}\boxed{p_j}} = \frac{N_p}{N_\star}\frac{1}{\langle p \rangle} = \frac{N_p}{N_\star^{\mathrm{eff}}}$$

Survey detection efficiency

(Zhu & Dong, 2021)

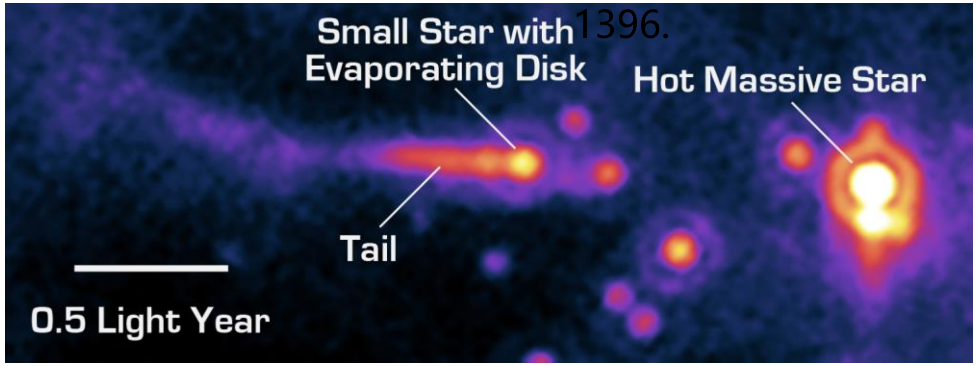
Photoevaporation



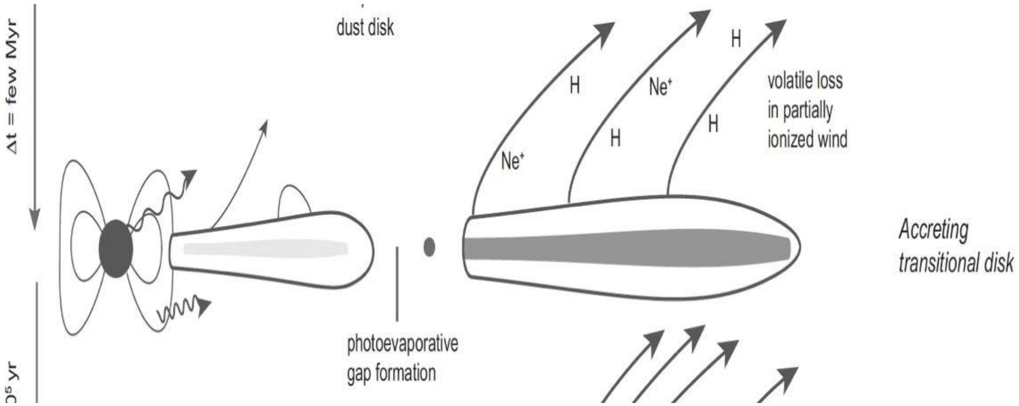
The pillar structure in Eagle nebula believed to be photoevaporated by nearby massive stars.

HST, NASA

A potential PPD being violently stripped by nearby O-type star in the star forming cloud IC 1396.



Spitzer telecope, NASA

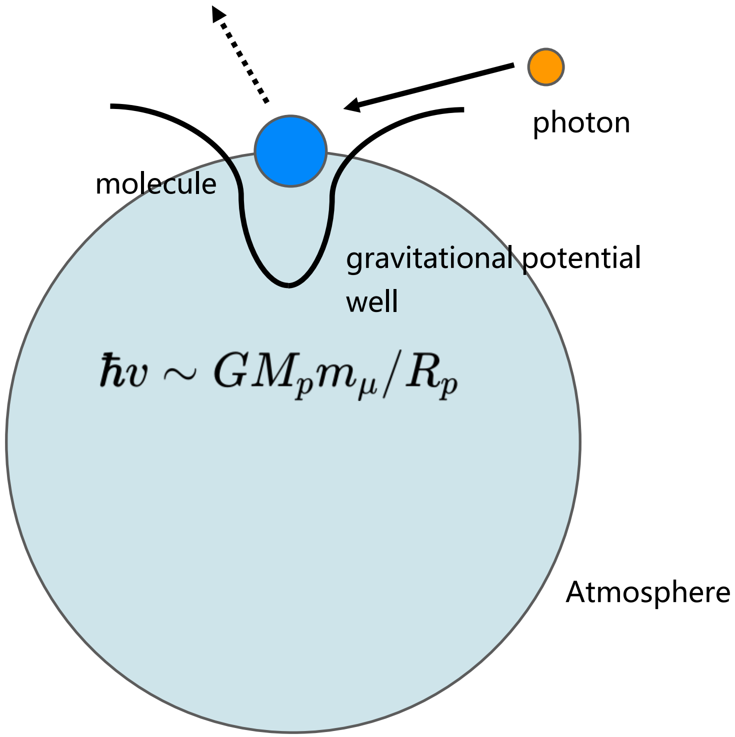


Photoevaporation causes disk dispersal within a typical time ~ 10Myrs

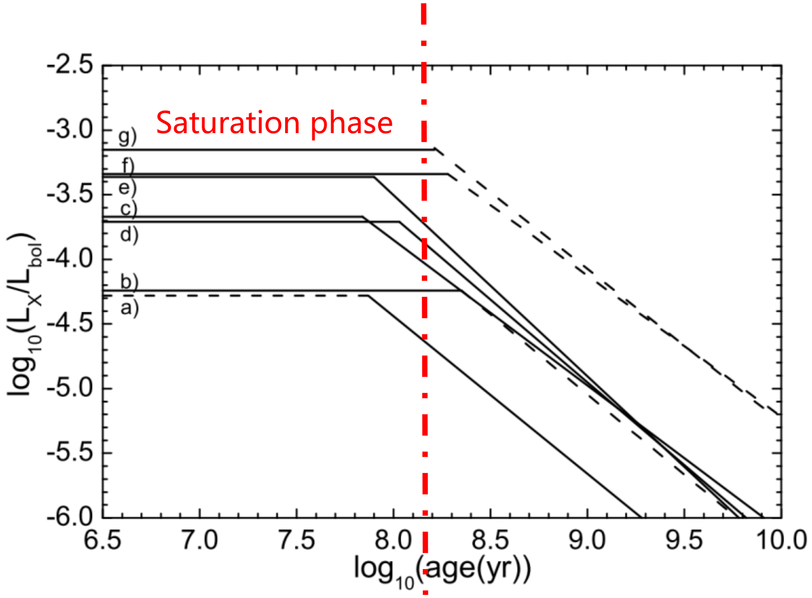
Light molecules being evaporated by high energy photons.

Photoevaporation

In the context of planetary atmosphere,



$$\hbar v \sim G M_p m_\mu / R_p$$



Jackson et al, MNRAS, 2012

High energy photons accelerate molecules, helping overcome planetary binding energy.

Generally, photoevaporation is mostly efficient for the **first ~100 Myrs** b/o the star is young and active.

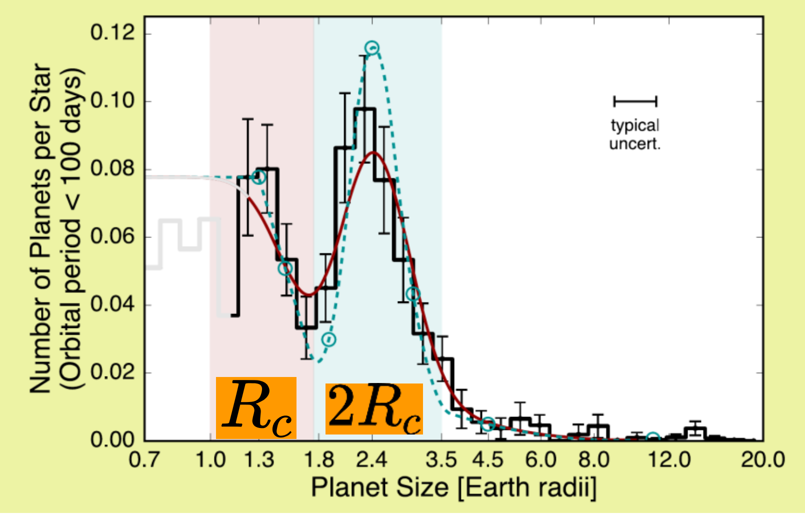
Erosion timescale:

$$t_{\dot{X}} = X/\dot{X} = M_{env}/\dot{M}_{env}$$

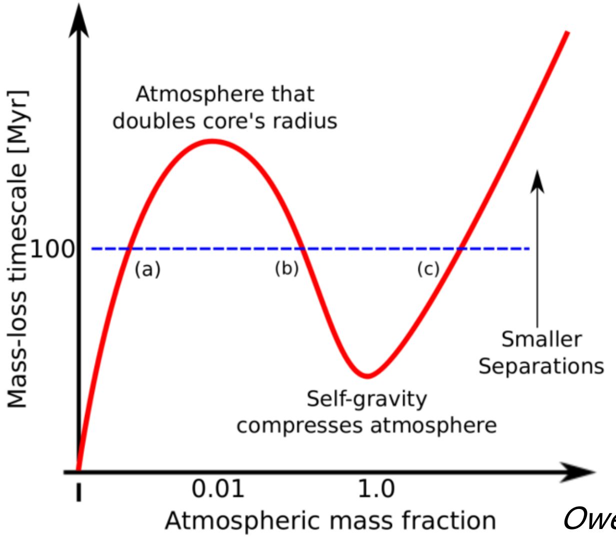
X : envelope mass fraction

M_{env} : photoevaporation rate

Take Home Message 1



Owen & Wu, ApJ, 2017



Owen, ARAA, 2019

Planets (Hot Jupiter) with very heavy atmosphere don't suffer from photoevaporation b/o the very deep gravitational well;
Planets (super earth) with thin atmosphere could be stripped bare considering low separation of Kepler samples, which leads to **the first peak on radius distribution**.

Planets (sub-Neptune) with H/He-rich envelopes that **double its radius** have the locally maximum envelope erosion timescale, which leads to **the second peak on radius distribution**.

Erosion Timescale

The key is to relate the erosion timescale with planetary **envelope size** given certain parameters (planet core mass, composition; star mass).

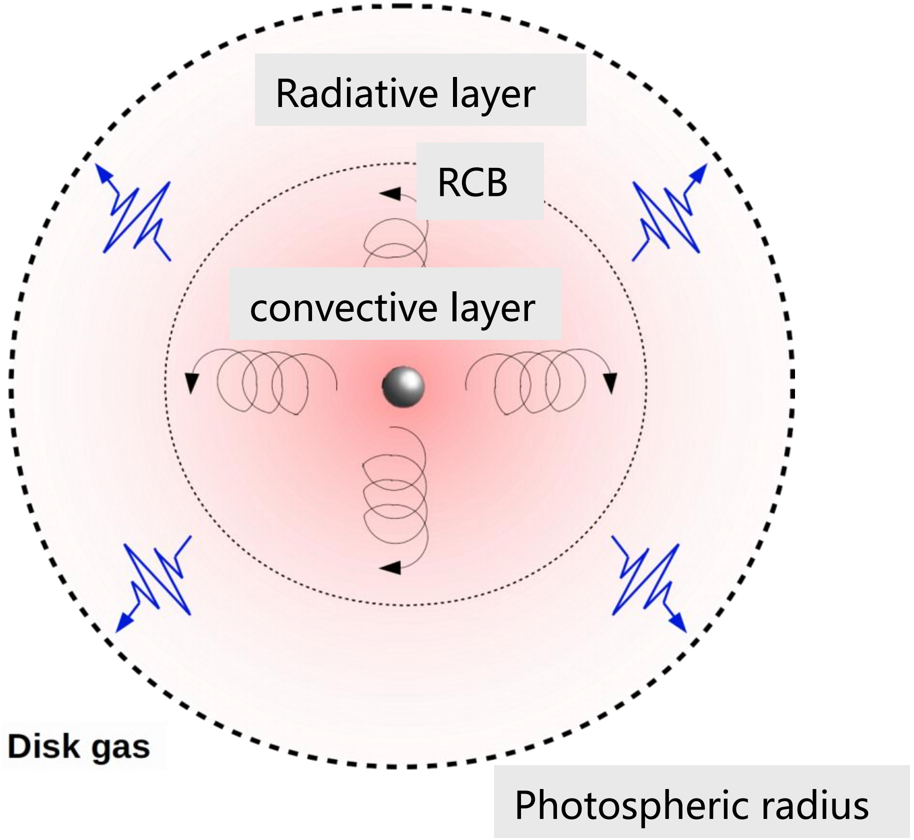
$$X = M_{env}/M_p = X(\Delta R)$$

Envelope mass is related to core mass (radius) by 1D modeling of planetary atmosphere.

- mass conservation
- hydrostatic balance
- luminosity equation (opacity law, KH contraction)
- equation of state
- planet density/composition assumption...

$$\dot{X} = \dot{M_{env}}/M_p = \dot{X}(L_{\rm HE}, a)$$

Evaporation rate is primarily related to **High energy photon luminosity** and **planet separation** from star.



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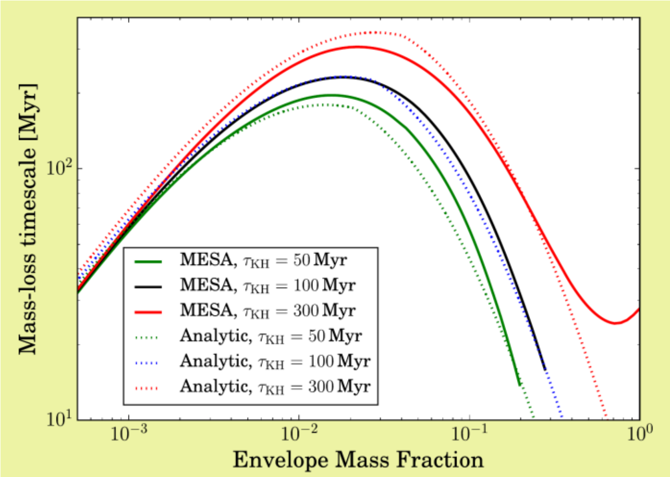
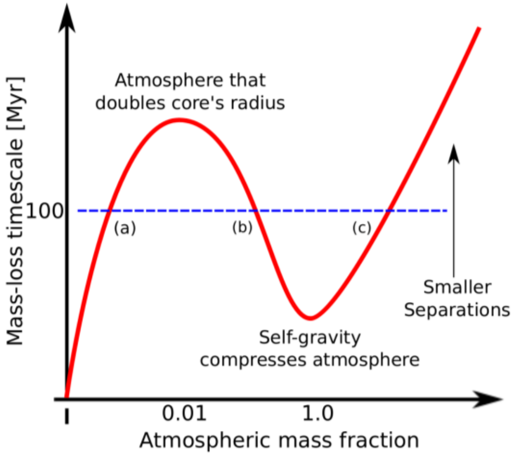
Erosion Timescale

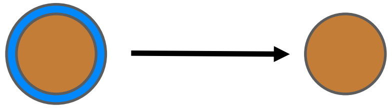


Owen & Wu, ApJ, 2017



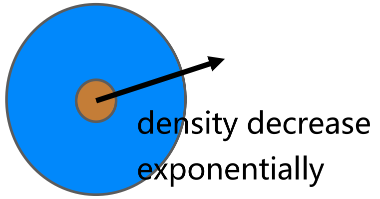
Owen, ARAA, 2019

To understand the trend:



Stripping regime (thin atmosphere):

Planet radii dominated by core radius -> losing mass causes the binding energy to decrease at surface -> continuous stripping of envelope.



Expansion regime (puff-up atmosphere):

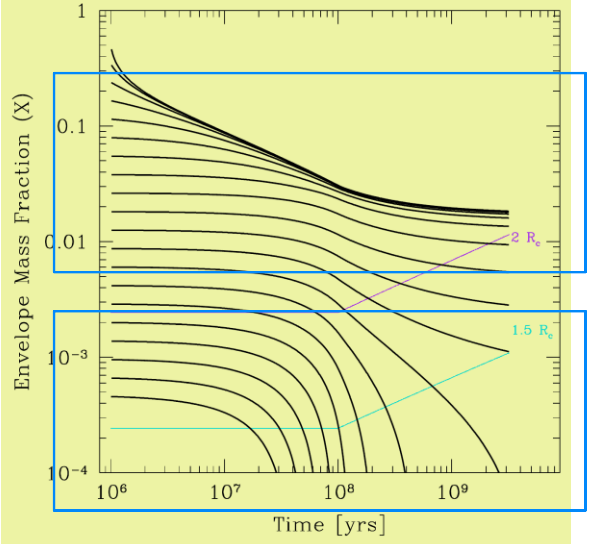
Planet radii swells up so fast ->facing much more HE flux -> net mass loss

Evaporation Valley

From single planet to a CKS sample:
Consider a group of planets spanning the typical parameter space of Kepler planets,

- initial core mass
- initial envelope fraction
- orbital period
- star's HE photon flux

Evolve them: $\frac{dX}{dt} = -\frac{X}{t_{\dot{X}}}.$

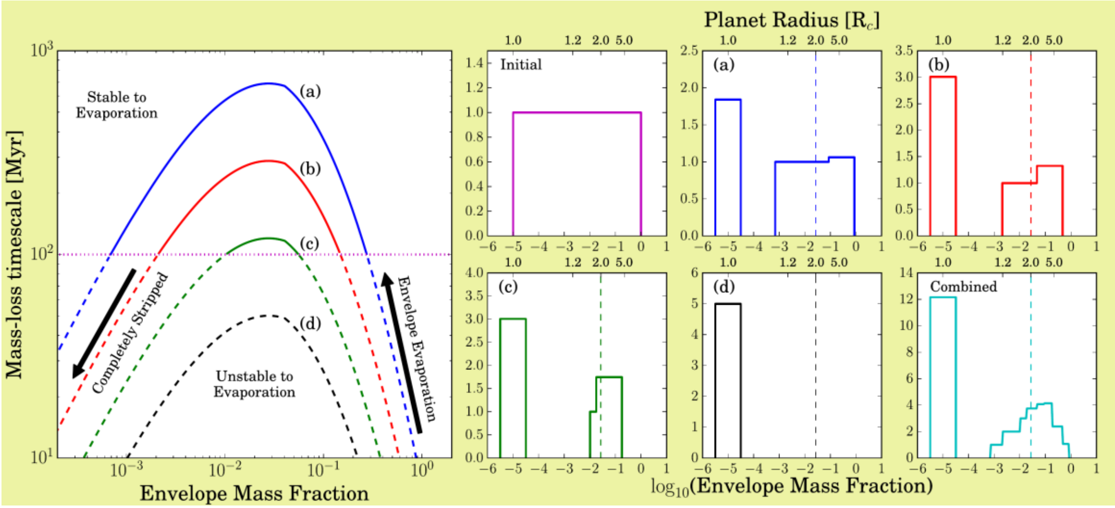


Shepherded to R ~ 2Rc

quickly stripped to a bare core. R ~ Rc

Owen & Wu, ApJ, 2017

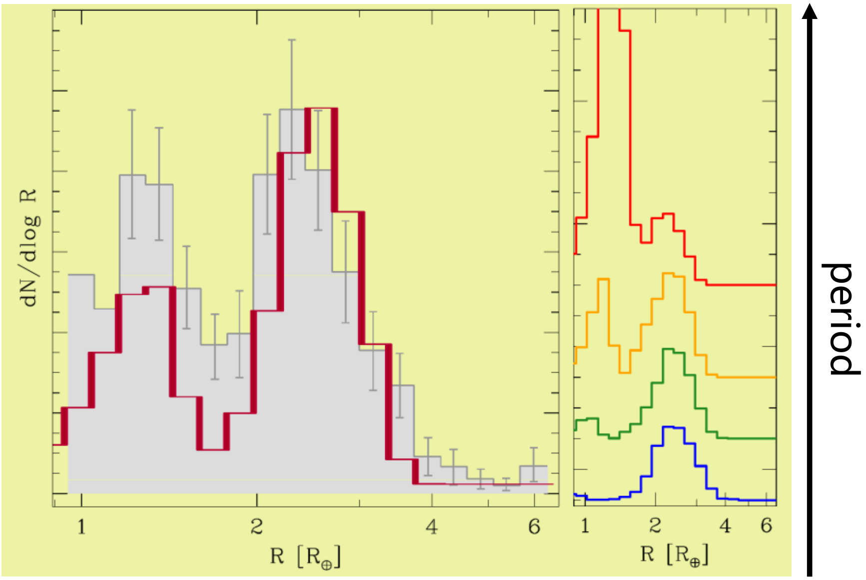
A demonstration on how radius valley emerges



Owen & Wu, ApJ, 2017

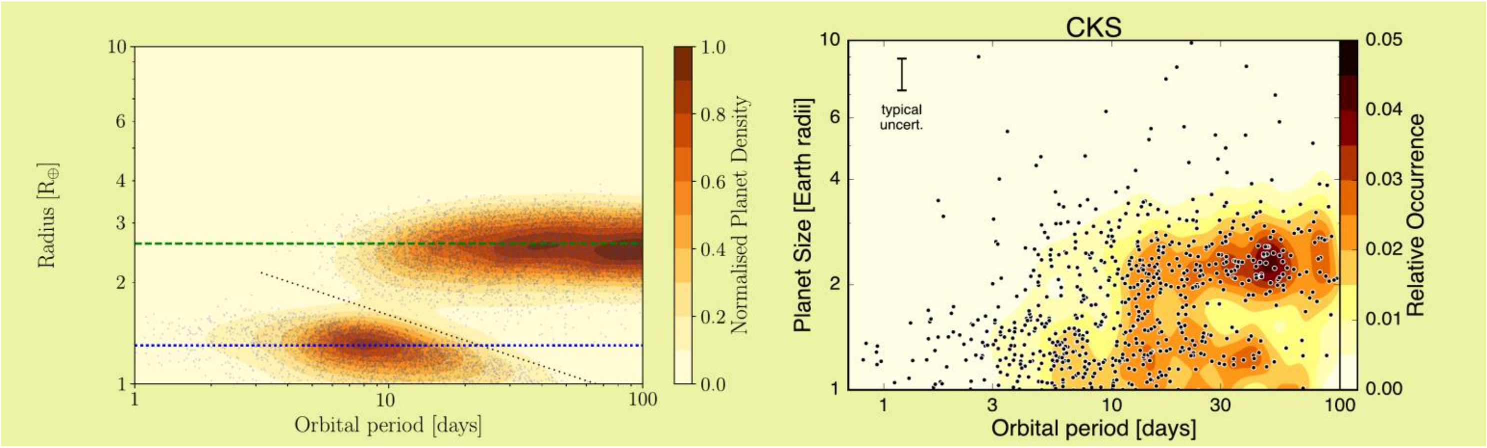
Evaporation Valley

1D distribution



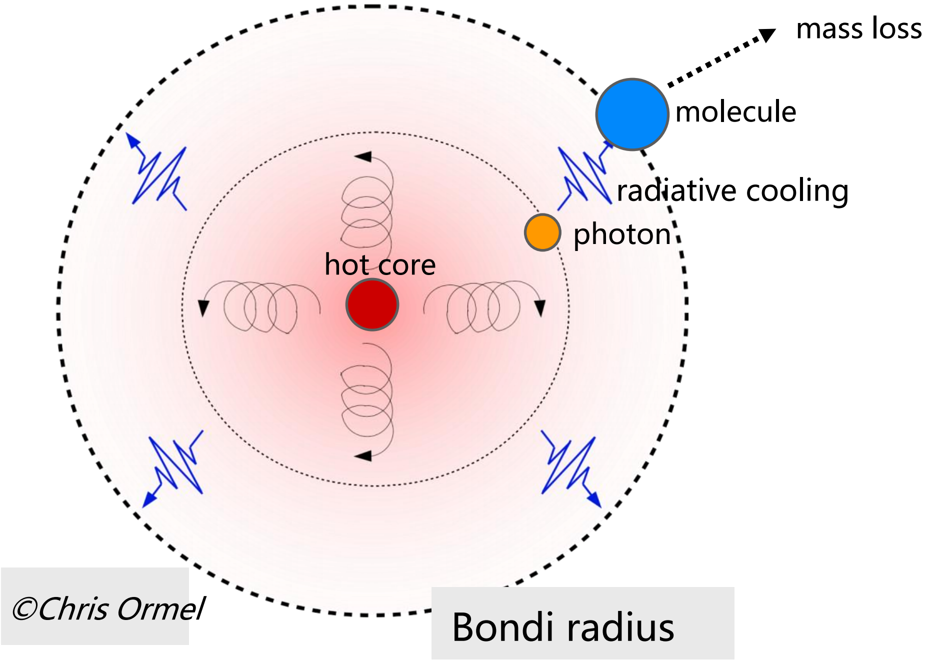
Owen & Wu, ApJ, 2017

2D distribution



Owen & Wu, ApJ, 2017

Core-powered Mass Loss



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$T_c \sim T_{atm}(R_c)$

Besides luminosity from the sun, **core itself cools down and radiates energy out.** The energy available is,

$$E_{cool} = g\Delta R(\boxed{\frac{\gamma}{2\gamma-1}M_{atm}} + \boxed{\frac{1}{\gamma}\frac{\gamma-1}{\gamma_c-1}\frac{\mu}{\mu_c}M_c),}$$

Atmosphere/ Core energy resevior

The energy needed to boil off whole atmosphere is,

$$E_{loss} \sim GM_cM_{atm}/R_c = M_{atm}gR_c.$$

Two ratio here is important:

$$\frac{E_{core}}{E_{atm}} \sim \frac{\mu}{\mu_c}\frac{M_c}{M_{atm}}$$

$$\frac{E_{atm}}{E_{loss}} \sim \frac{\Delta R}{R_c}$$

Core-powered Mass Loss

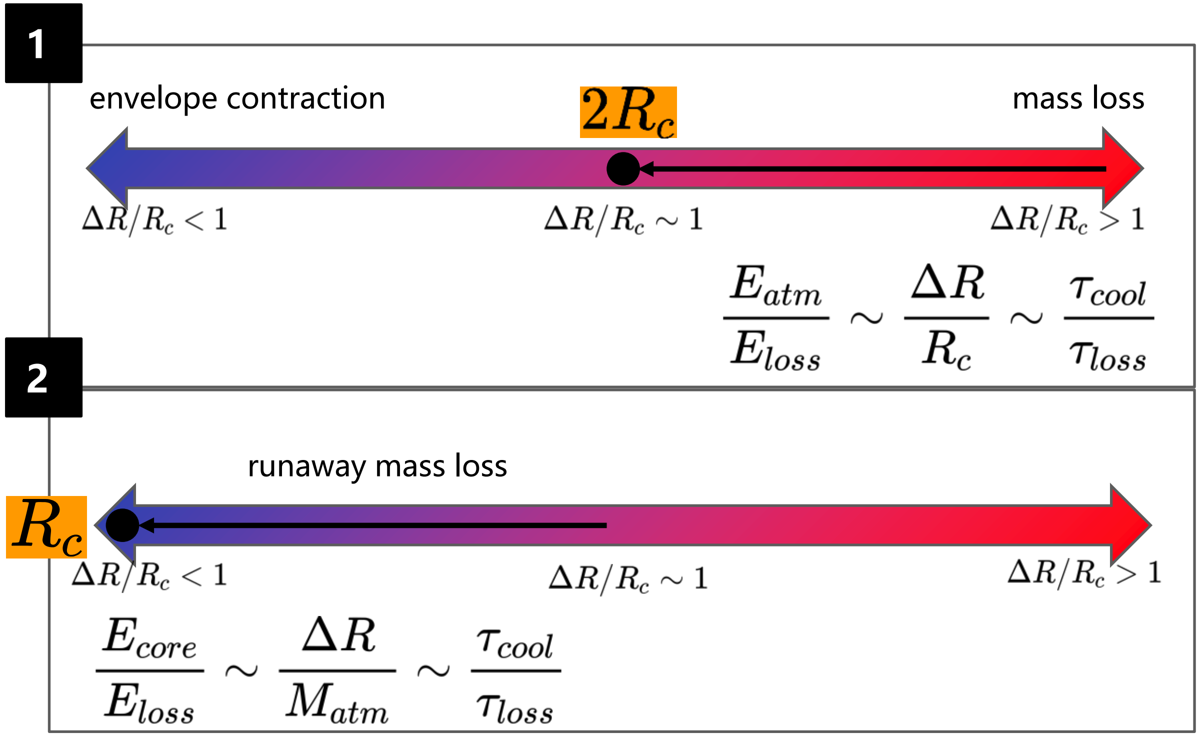
Bifurcation point:

$$\frac{E_{core}}{E_{atm}} \sim \frac{\mu}{\mu_c}\frac{M_c}{M_{atm}}$$

>1 → 1. Heavy atmosphere

<1 → 2. Thin atmosphere

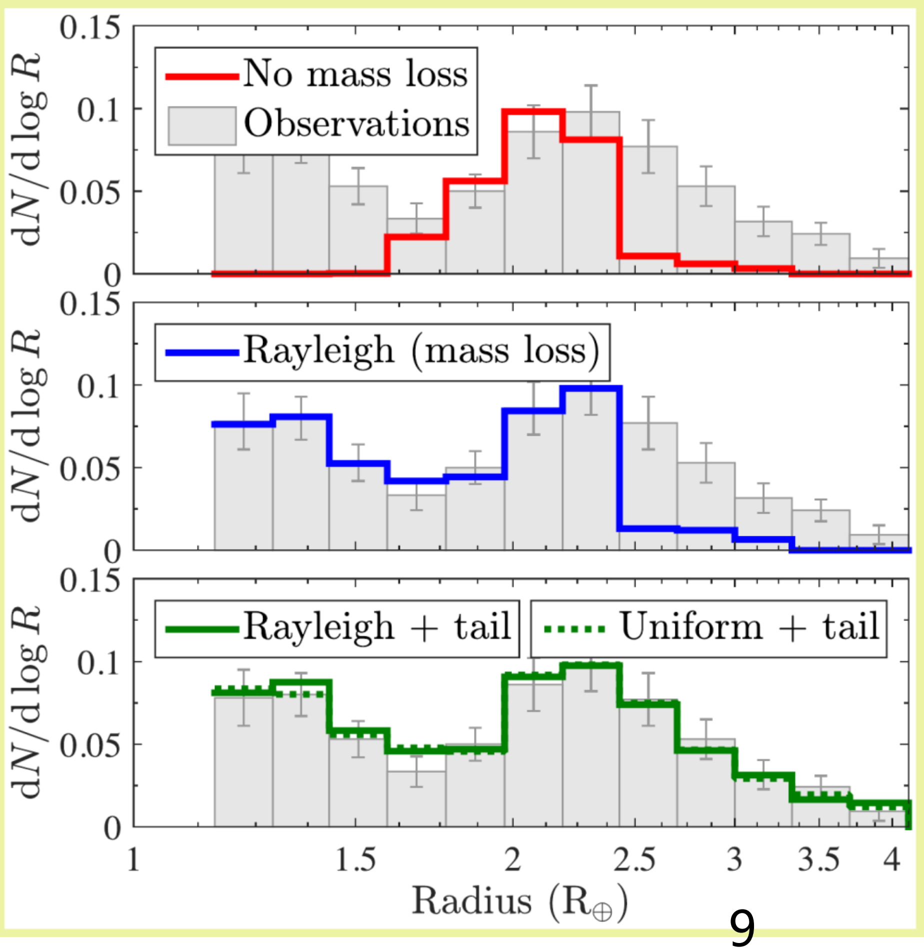
τ_{cool} v.s. τ_{loss}



$$\frac{E_{atm}}{E_{loss}} \sim \frac{\Delta R}{R_c} \sim \frac{\tau_{cool}}{\tau_{loss}}$$

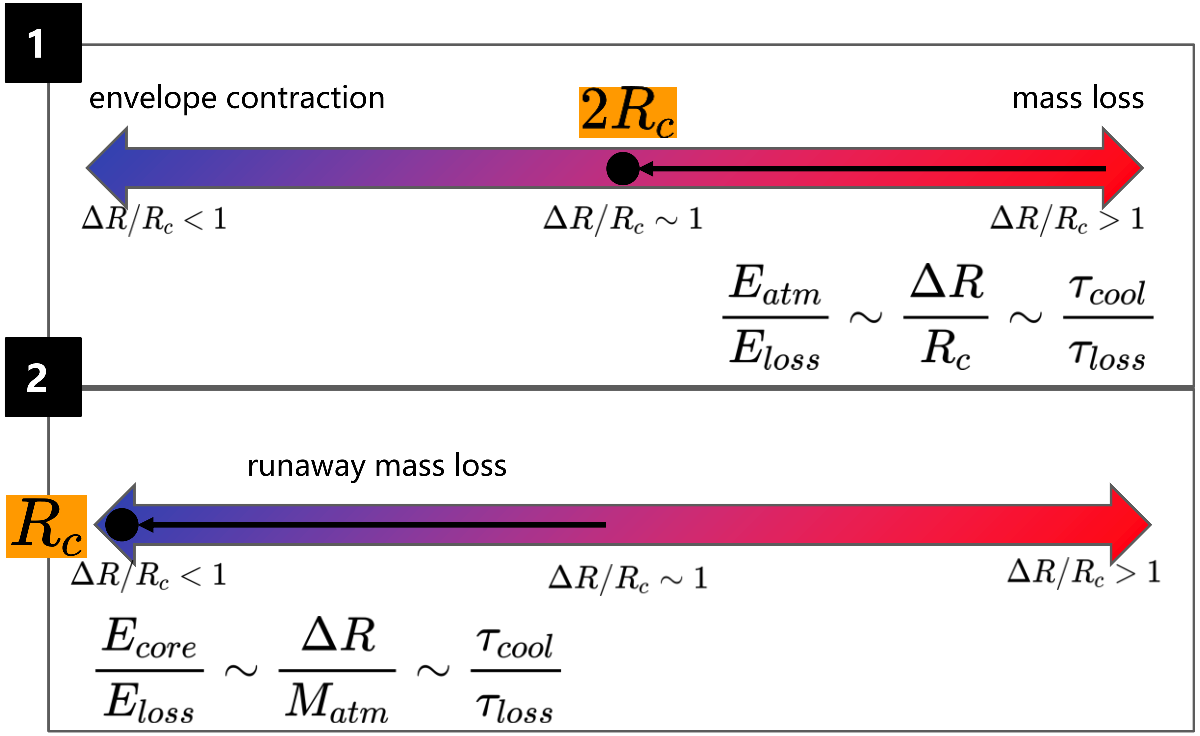
$$\frac{E_{core}}{E_{loss}} \sim \frac{\Delta R}{M_{atm}} \sim \frac{\tau_{cool}}{\tau_{loss}}$$

Sampling result of different core mass distribution



Ginzburg et al, MNRAS, 2019

Take Home Message 2



1

envelope contraction

$2R_c$

mass loss

$\Delta R/R_c < 1$ $\Delta R/R_c \sim 1$ $\Delta R/R_c > 1$

$$\frac{E_{atm}}{E_{loss}} \sim \frac{\Delta R}{R_c} \sim \frac{\tau_{cool}}{\tau_{loss}}$$

2

runaway mass loss

R_c

$\Delta R/R_c < 1$ $\Delta R/R_c \sim 1$ $\Delta R/R_c > 1$

$$\frac{E_{core}}{E_{loss}} \sim \frac{\Delta R}{M_{atm}} \sim \frac{\tau_{cool}}{\tau_{loss}}$$

Planets (super earth) with core luminosity dominating the cooling process can blow off its thin envelope, which corresponds to **the first peak on radius distribution**.

Planets (sub-Neptune) with envelope luminosity dominating the cooling process contract, which shepherd its radius to **the second peak,** and stay intact.

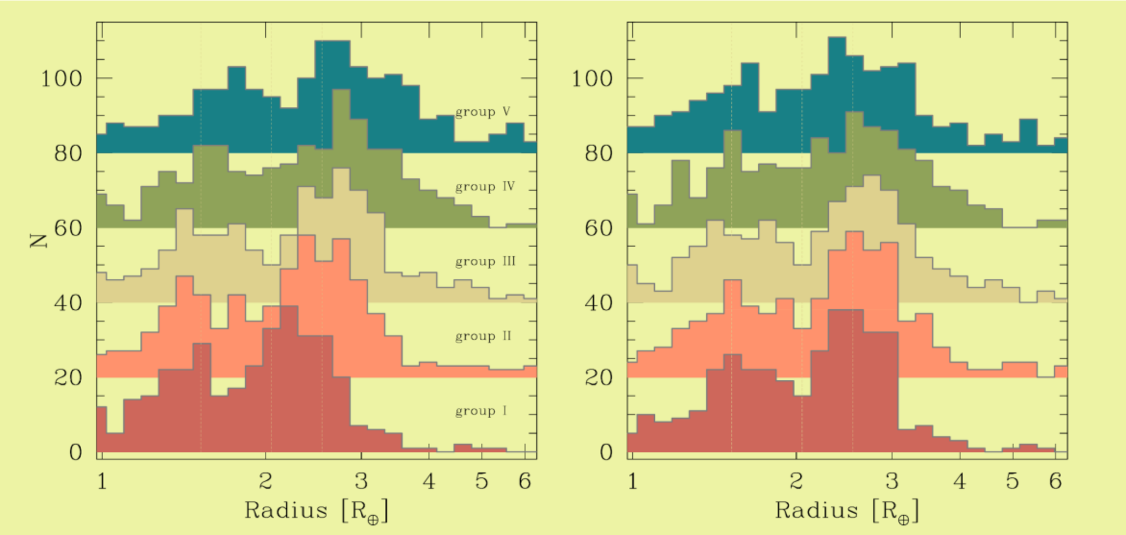
Stellar Mass Dependence: Born to be or Evolutive?

Photoevaporation

The total High-energy flux received by a planet for initial ~100Myrs is not observationally accessible for individual planet. (Our earth is >4Gyrs old)

Thus it is severely model-dependent...

Instead, Wu 2019 suggests an intrinsic planet-Star mass relation to explain the observed valley position shift with varied stellar mass.



Wu, ApJ, 2019

scaled planet Radius (with star mass)

$$\mu = \frac{M_p}{M_*} \approx 2.5 \times 10^{-5}\left(\frac{M_*}{M_\odot}\right)^a\left(\frac{Z_*}{Z_\odot}\right)^b\left(\frac{r}{0.1au}\right)^\gamma$$

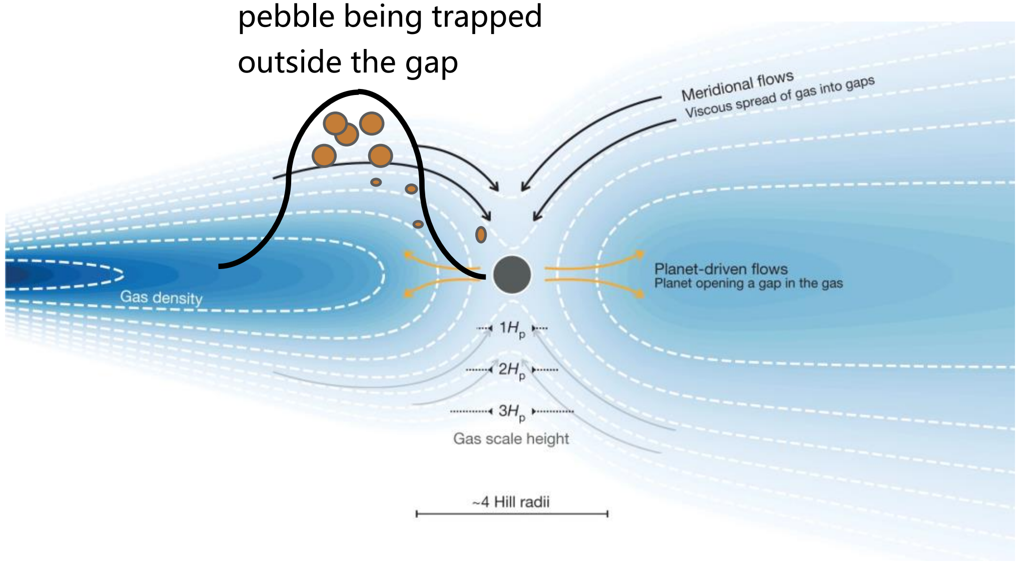
$$a \in [-0.05, 0.35] \qquad b \sim 0$$

Stellar Mass Dependence: Born to be?

Photoevaporation

Kepler planets follow its thermal mass($H \sim R_{Hill}$)?

Armitage & Rice, 2005



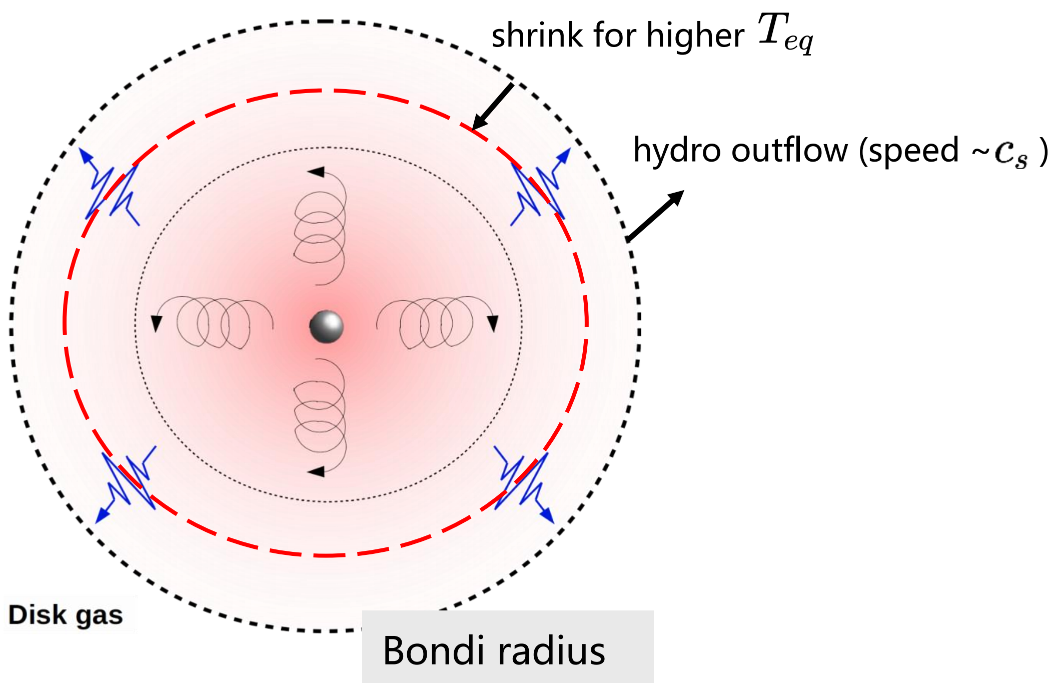
pebble being trapped outside the gap

Teague et al, 2019

The estimated *a* for thermal mass is ~ 1.375, lying in the region suggested by observations.

Stellar Mass Dependence: Evolutive?

Core-powered mass loss



The mass losing rate is limited by material supply by hydro flow:

$$|\dot{M}_{atm}| < \dot{M}^{B}_{atm} \equiv 4\pi R_B^2 \rho(R_B) c_s,$$

$$\dot{M}^{B}_{atm} = 4\pi R_B^2 c_s \rho_{rcb} \boxed{exp(-\frac{R_B}{R_{rcb}}).}$$

$$R_B = \frac{GM_p}{c_s^2} \qquad c_s = \sqrt{\frac{k_B T_{eq}}{\mu m_p}}$$

Higher stellar mass -> Higher T_eq -> Higher mass losing rate -> the valley shifts to larger radius.

$$\frac{d\log R_p}{d\log M_*} = 0.33$$

Other Parameters

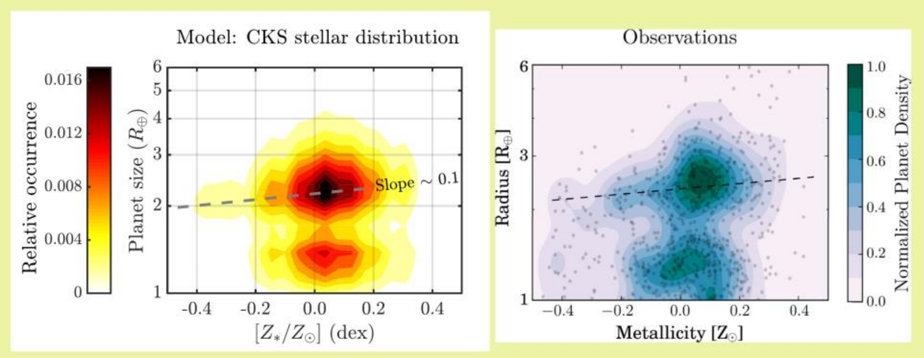
2. stellar metallicity

Core-powered mass loss

influence the opacity of envelope -> energy losing efficiency(τ_{KH}) of sub-Neptunes.

Photoevaporation

negligible



Gupta & Schlichting, MNRAS, 2020

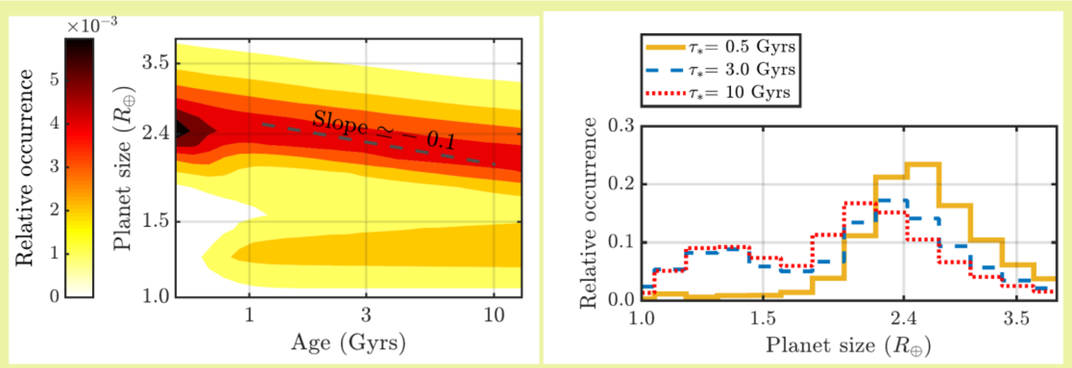
3. stellar age dependence

Both

operation timescale:

>Gyrs v.s. **100Myrs**

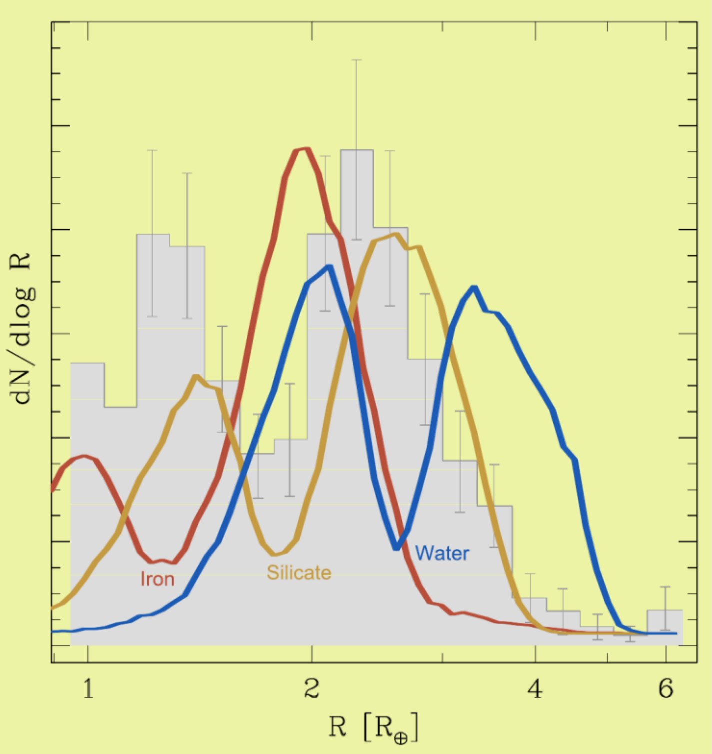
More sub-Neptunes become super earths with the characteristic timescale.



Gupta & Schlichting, MNRAS, 2020

Implications on core composition

Sampling results for different core composition assumptions



Owen & Wu, ApJ, 2017

-> Earth-like composition for CKS sample

If we know the composition of different groups precisely, we can imply planet mass from its radius measurements.

Summary

- Both photoevaporation model (Owen & Wu, 2017) and core-powered mass loss model (Ginzburg et al, 2018) can explain the observed valley at ~ 2 earth radius from CKS data.
- The two models vary from many aspects, implying further observation practices to distinguish them,
  - Correlations between planet and stellar mass.
  - Slope of the radius valley as a function of stellar mass (or luminosity).
  - Relative abundance of super-Earths and sub-Neptunes as a function of age.
  - Planets in the gap.

Observational evidences of the two models

Xiao Li **Advisor: Wei Zhu**

Collaborators: Xiaoyi Ma, Yu Wang, Zhaoning Liu

May 27, 2022

清華大學天文系
Department of Astronomy, Tsinghua University

Outline

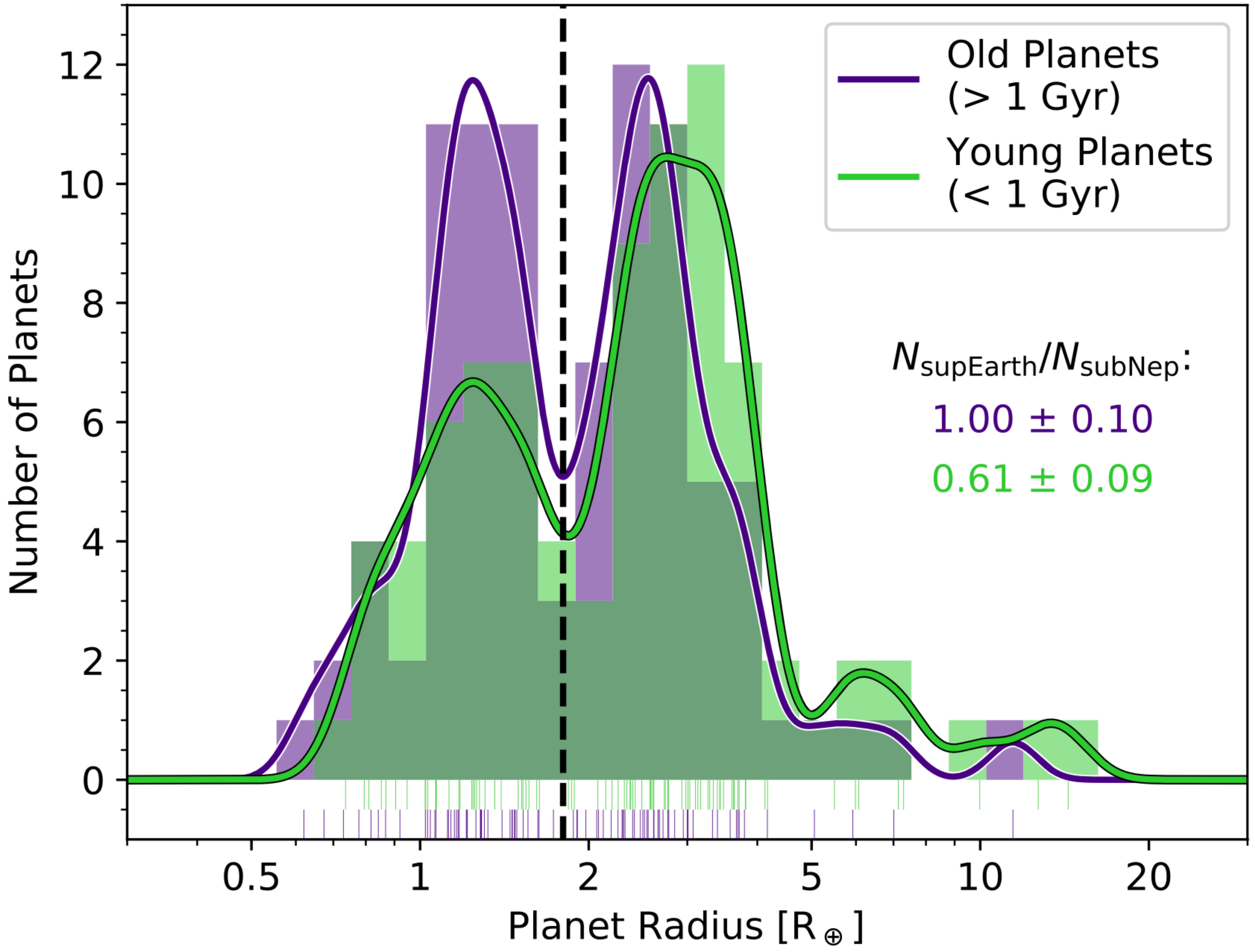
The dependence of planet radius distribution on

- Stellar age
- Stellar mass
- Orbital period
- Insolation
- Metallicity

Summary

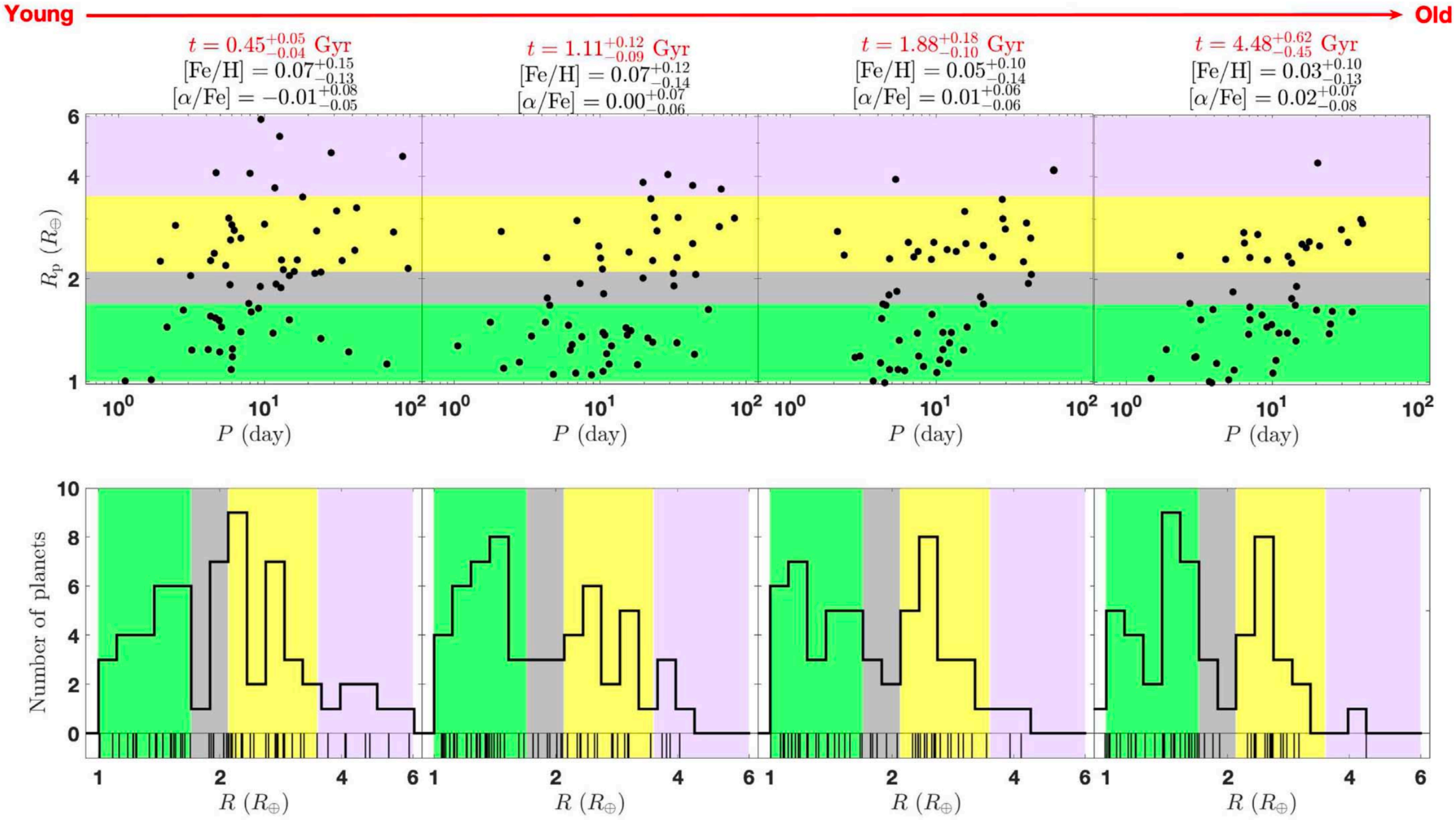
Planet radius distribution as a function of stellar age

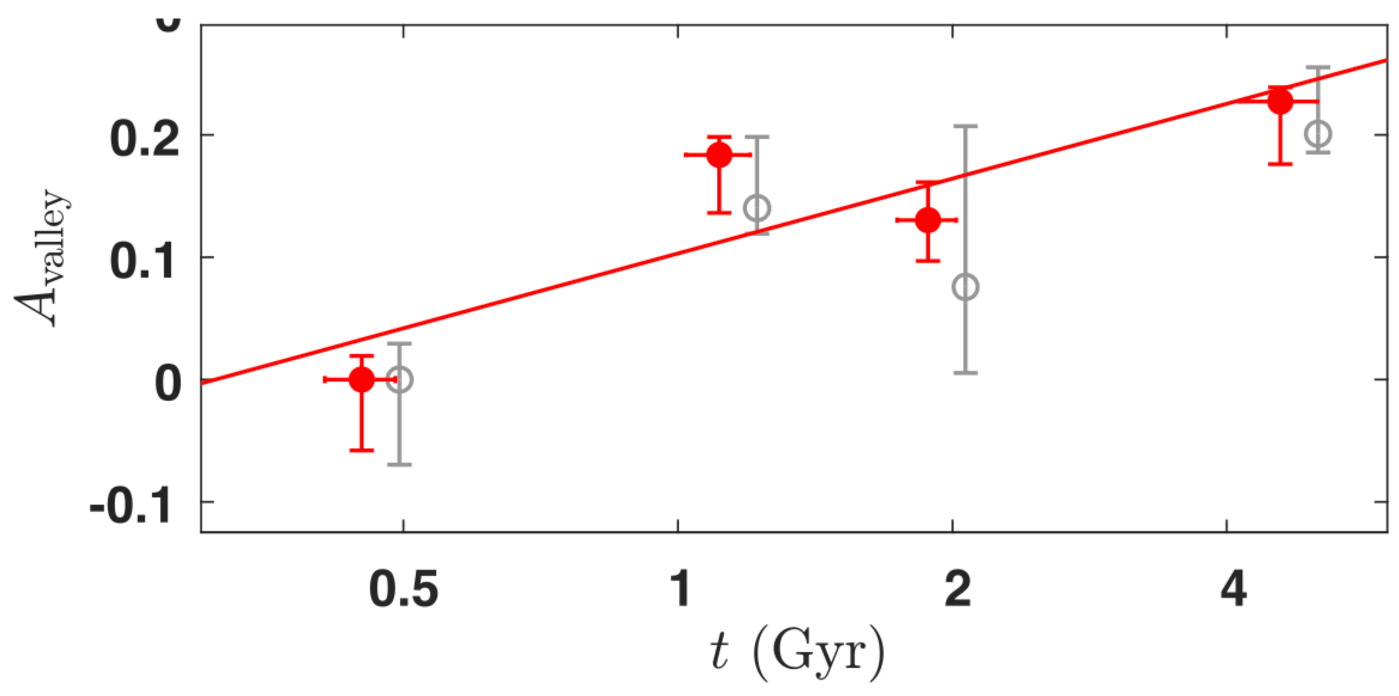
- The relative abundance of super-Earth to sub-Neptune increases with time
- Sub-Neptunes evolve to become super-Earths over Gyr timescales, consistent with core-powered mass loss model
- The location of the gap does not show significant movement



Berger+2020

Planet radius distribution as a function of age



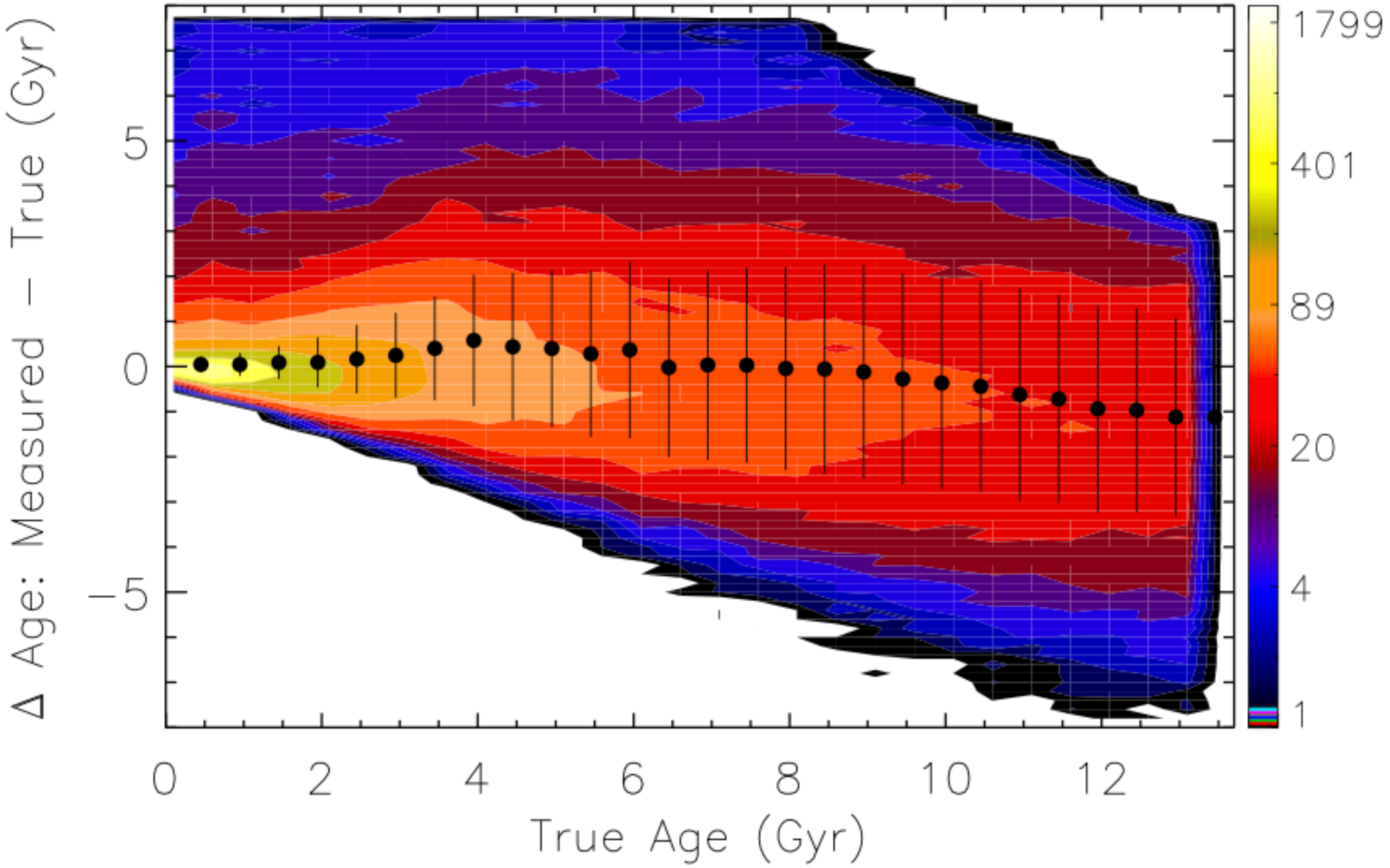


$$A_{valley} = \log_{10}\frac{N_{SE}}{N_{SN}}$$

SE : super-Earth
SN : sub-Neptune
VP : valley planet

Chen+2022

Large uncertainties in the stellar age estimation


Isochrone age

Xiang+2022

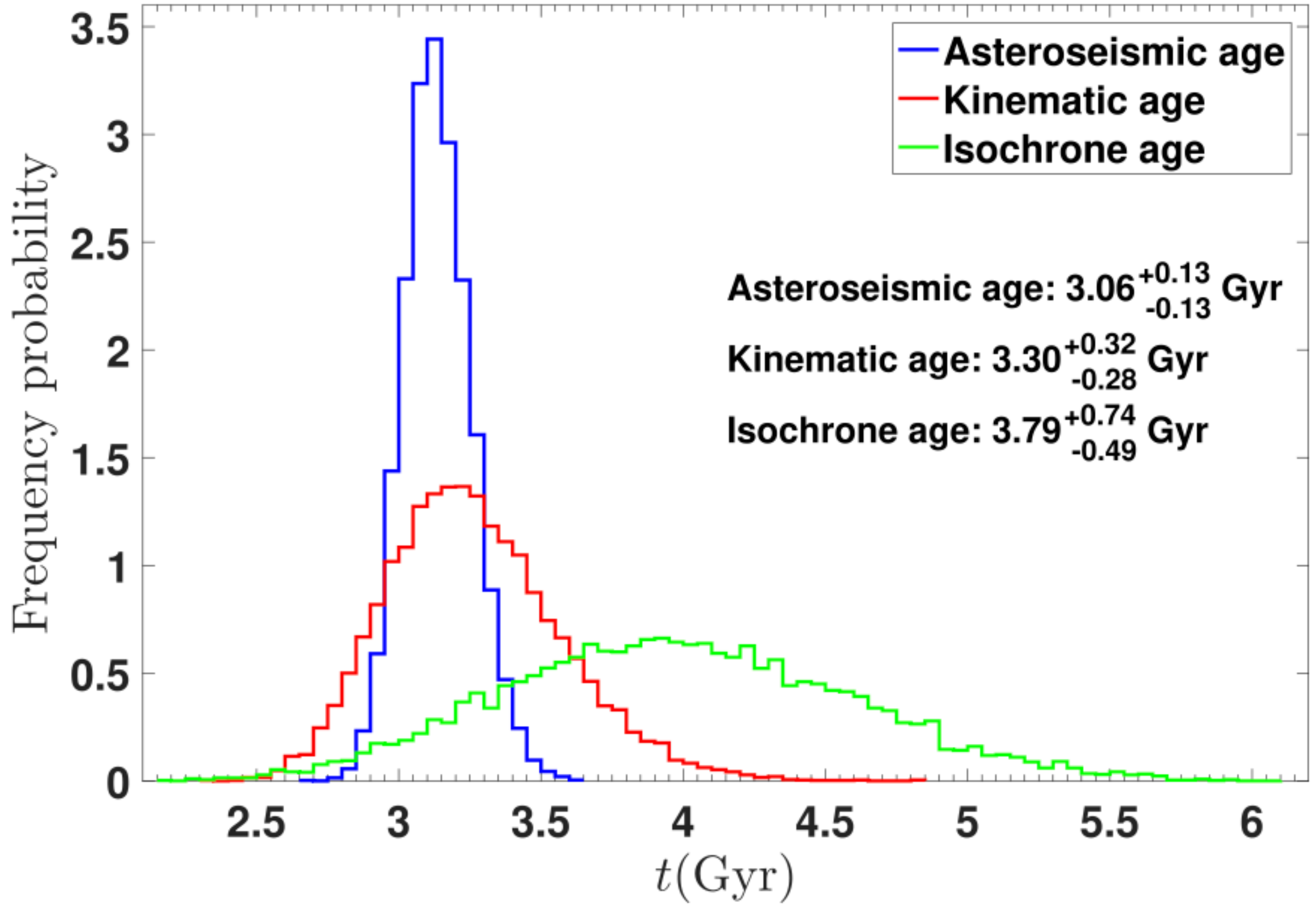


Figure 20. Distributions of the asteroseismic age (blue), kinematic age (red) and isochrone age (green) of 54 Kepler stars.

Chen+2022

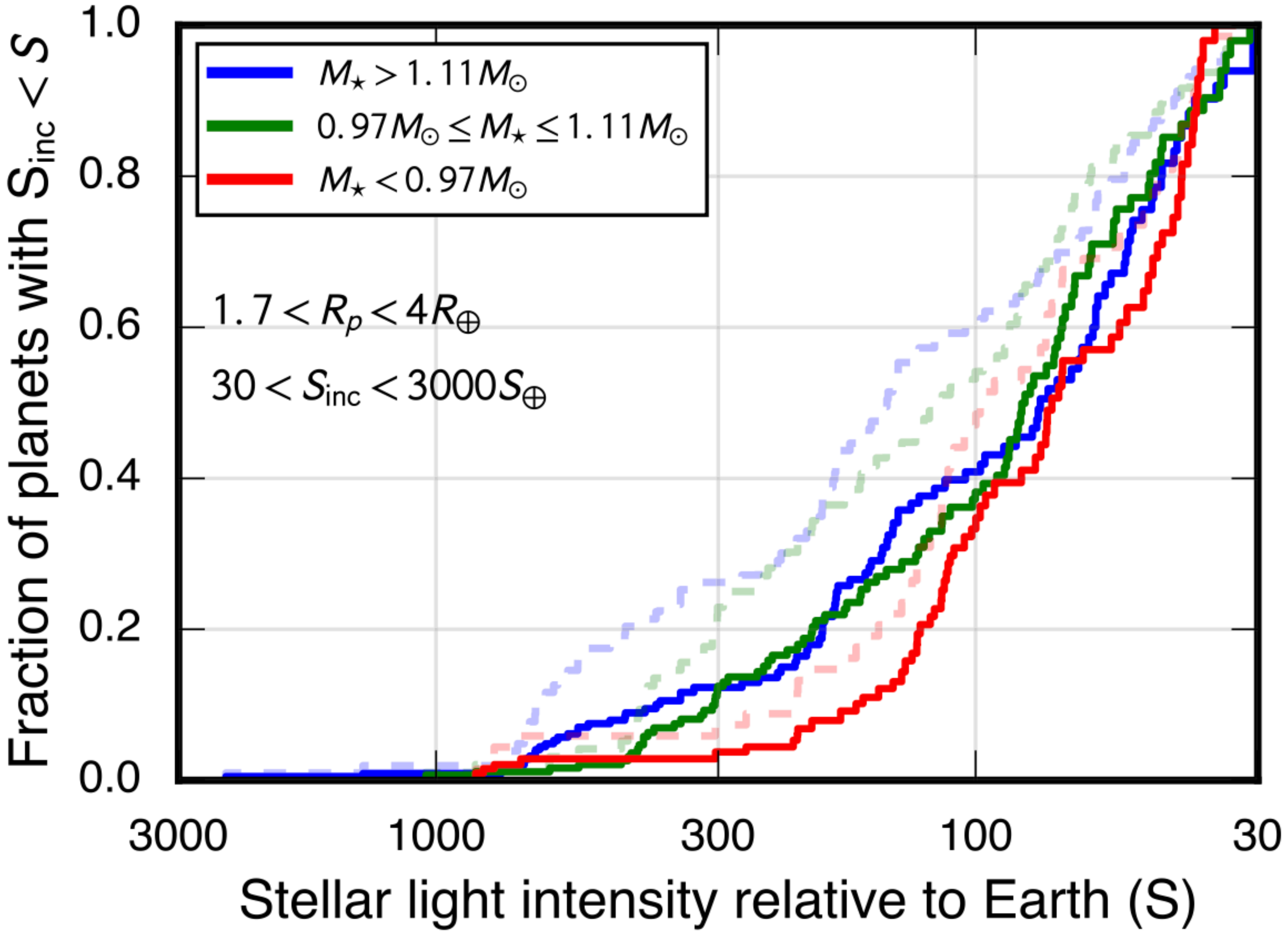
Dependence on stellar mass

- Photoevaporation

  - More relevant to XUV incident flux, which is stronger around lower-mass stars
  - The population of sub-Neptunes should shift to lower insolation with decrease stellar mass

- Core-powered mass loss

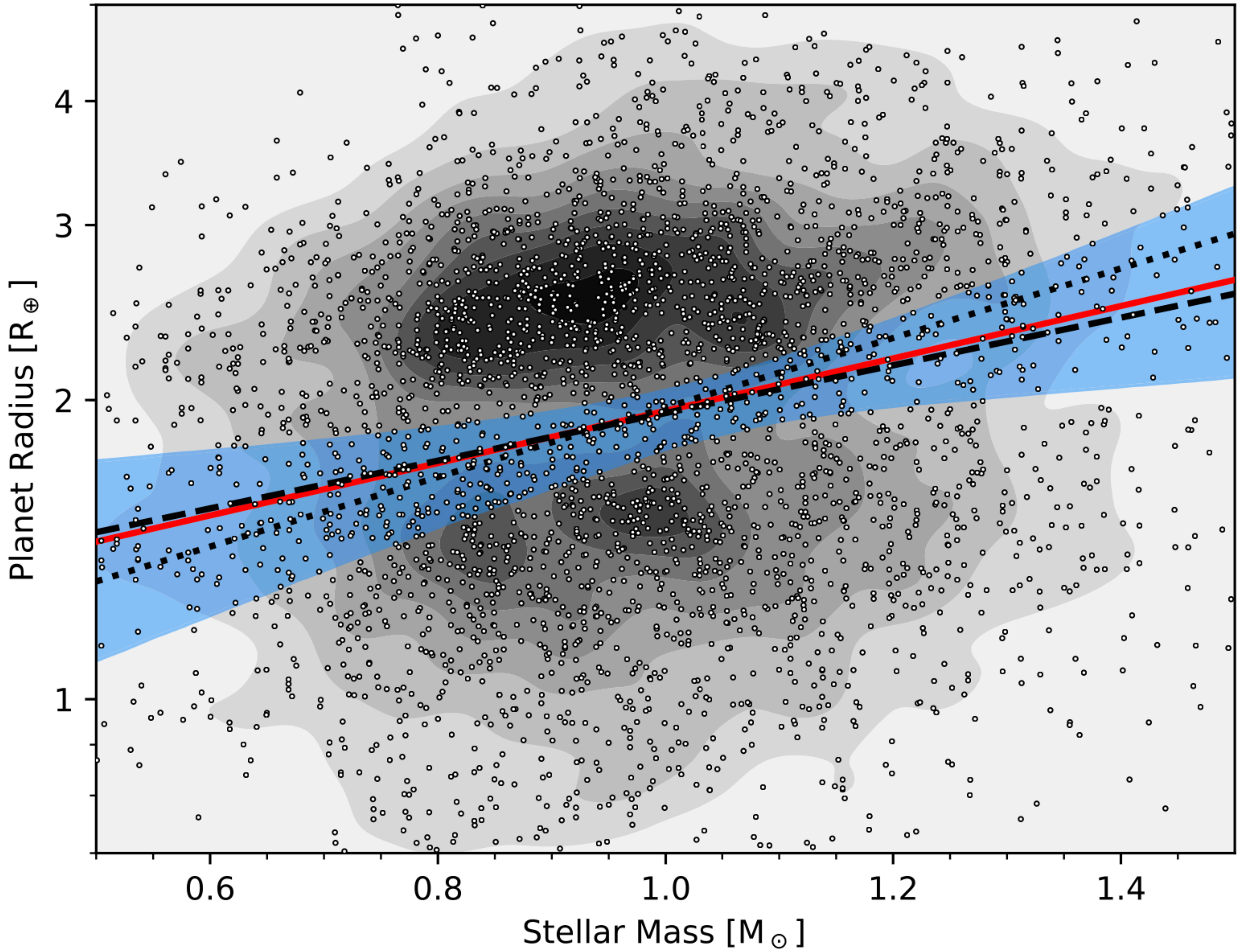
  - Relevant to the bolometric incident stellar flux
  - No dependence of the planet population on stellar mass



Fulton & Petigura 2018

Dependence on stellar mass

- The slope is $\frac{d\log R_p}{d\log M_*} = 0.26^{+0.21}_{-0.16}$
- Core-powered mass loss $\frac{d\log R_p}{d\log M_*} \sim 0.33$
- Photoevaporation : $\frac{d\log R_p}{d\log M_*} \in [-0.05,\, 0.35]$

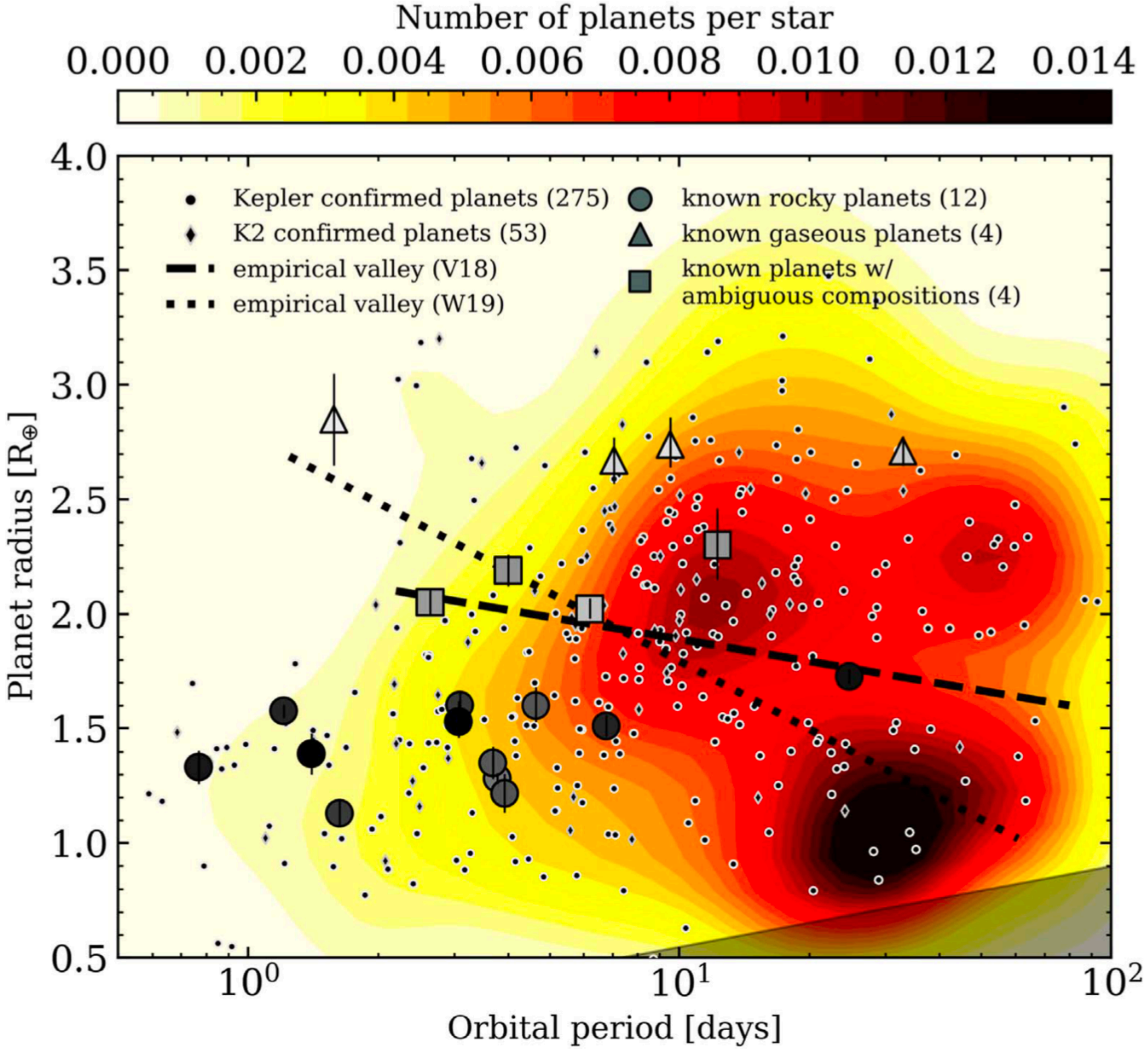


Berger+2020

planet radius - orbital period

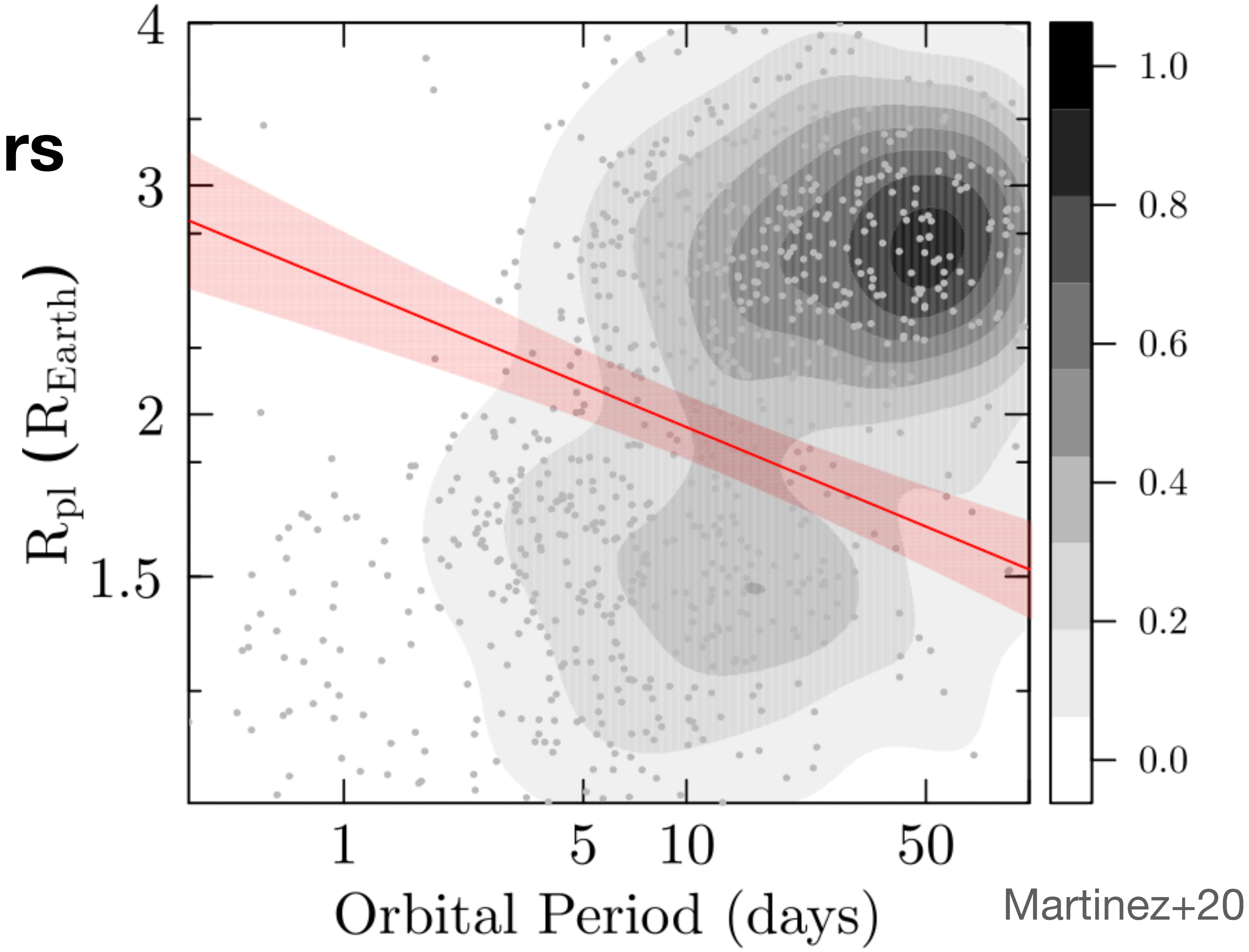
A negative correlation

M-dwarfs

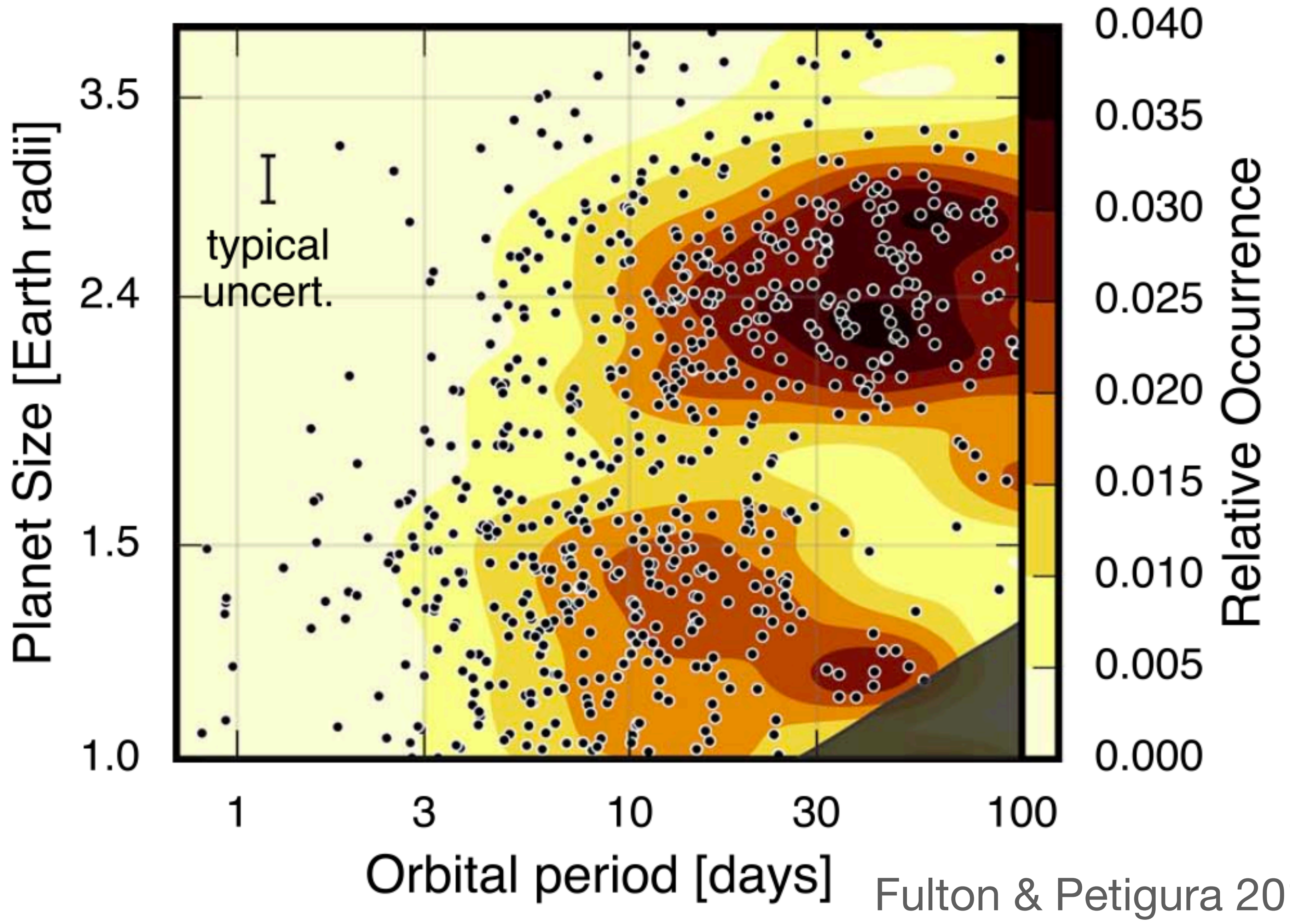


Cloutier & Menou 2020

Sun-like stars



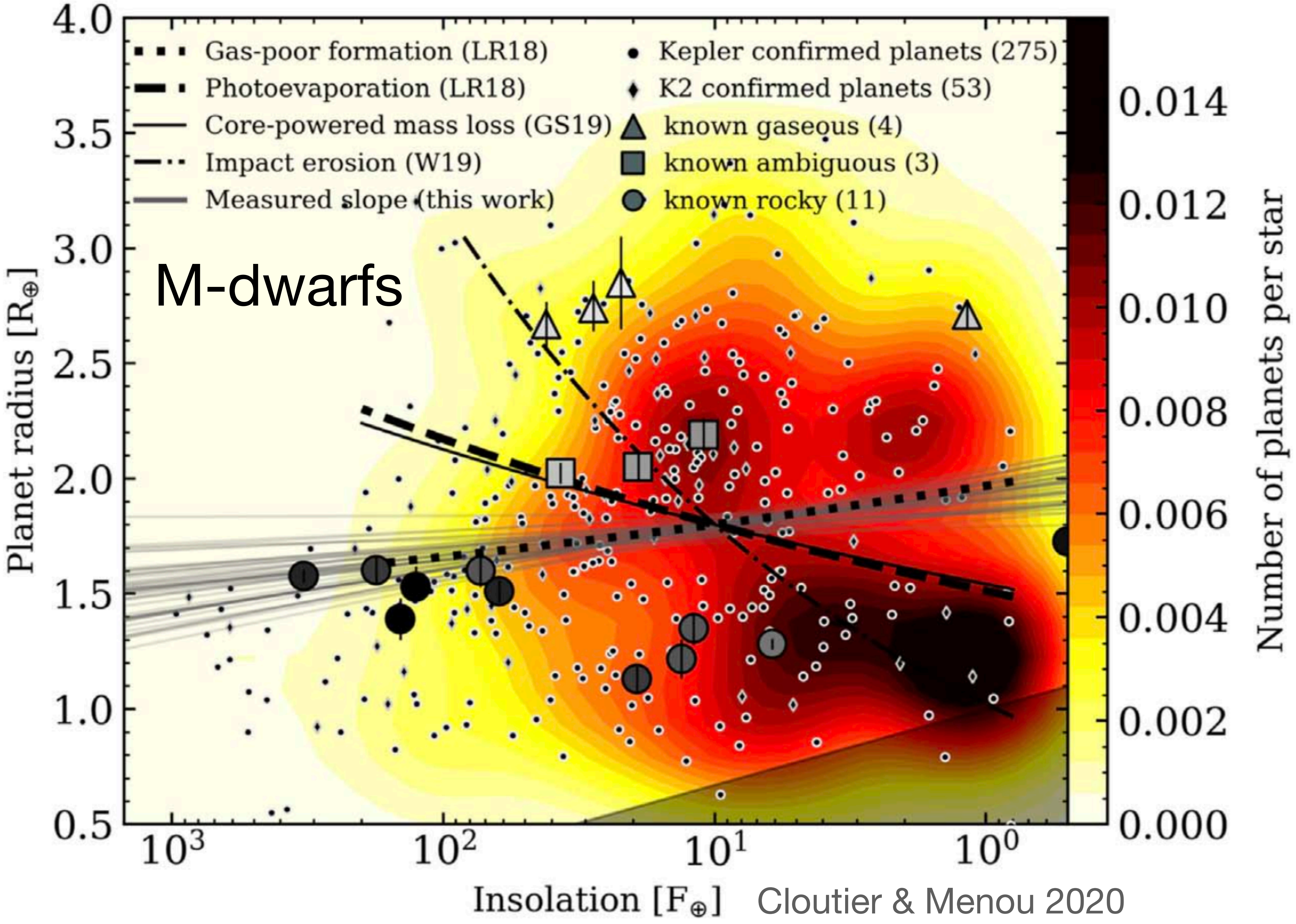
Martinez+2019



Fulton & Petigura 2018

The location of the radius valley as a function of insolation

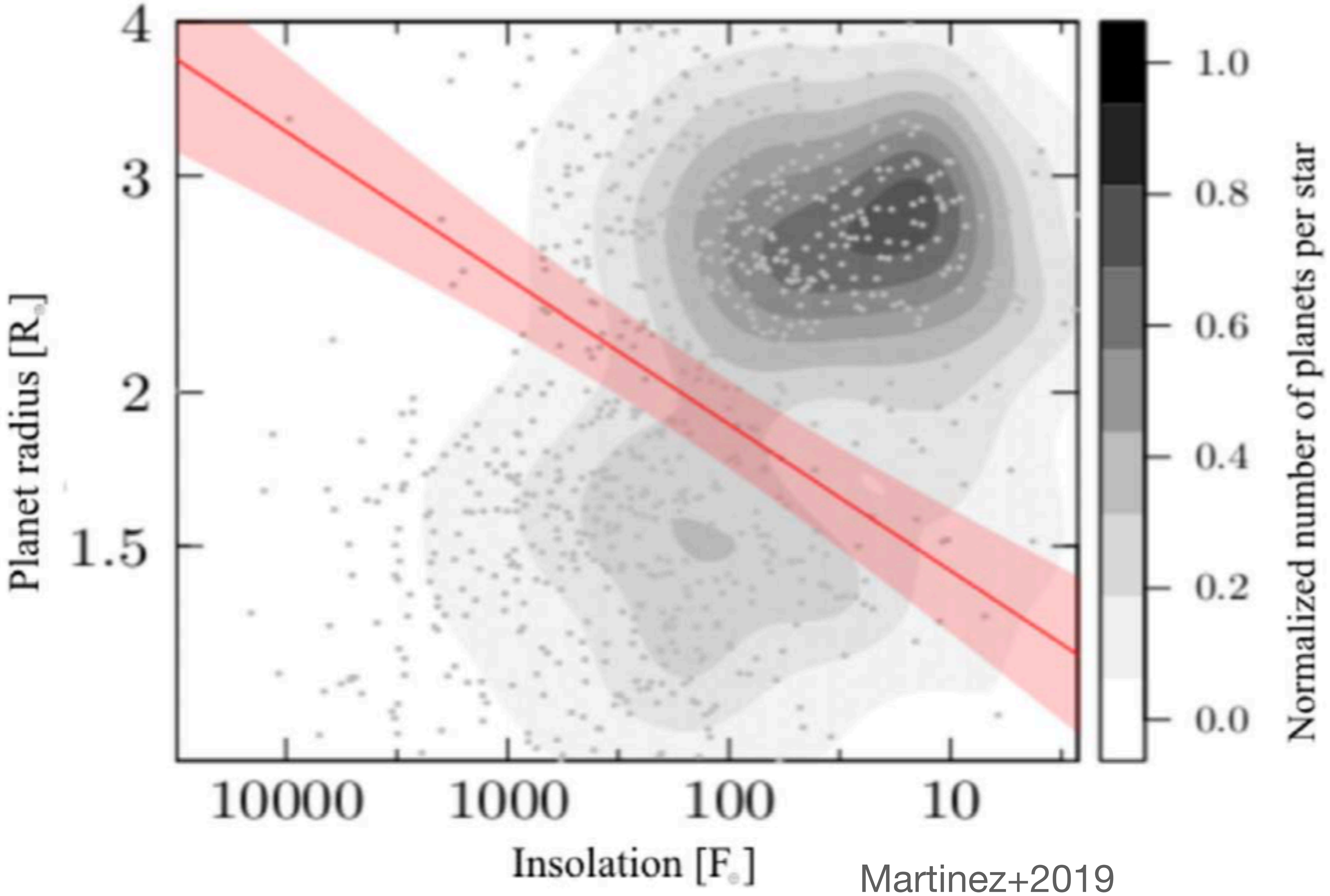
- For sun-like stars, both photoevaporation and core-powered mass loss can predict this relation well consistent with observations
- For M-dwarfs, the gas-poor formation model may play a role
- It’ll be interesting to examine the relation between planet radius and XUV flux



M-dwarfs

Cloutier & Menou 2020

Sun-like stars

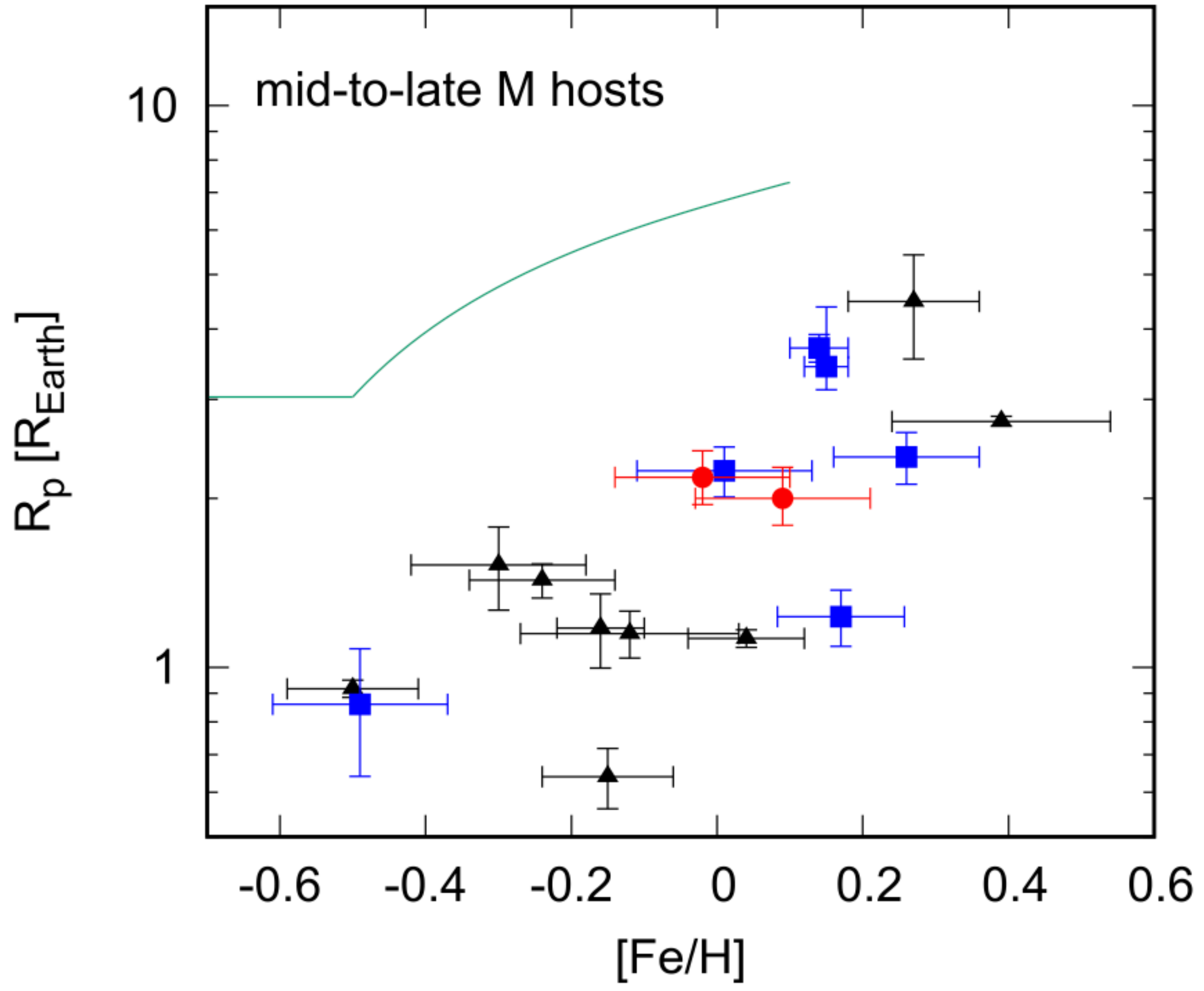


Martinez+2019

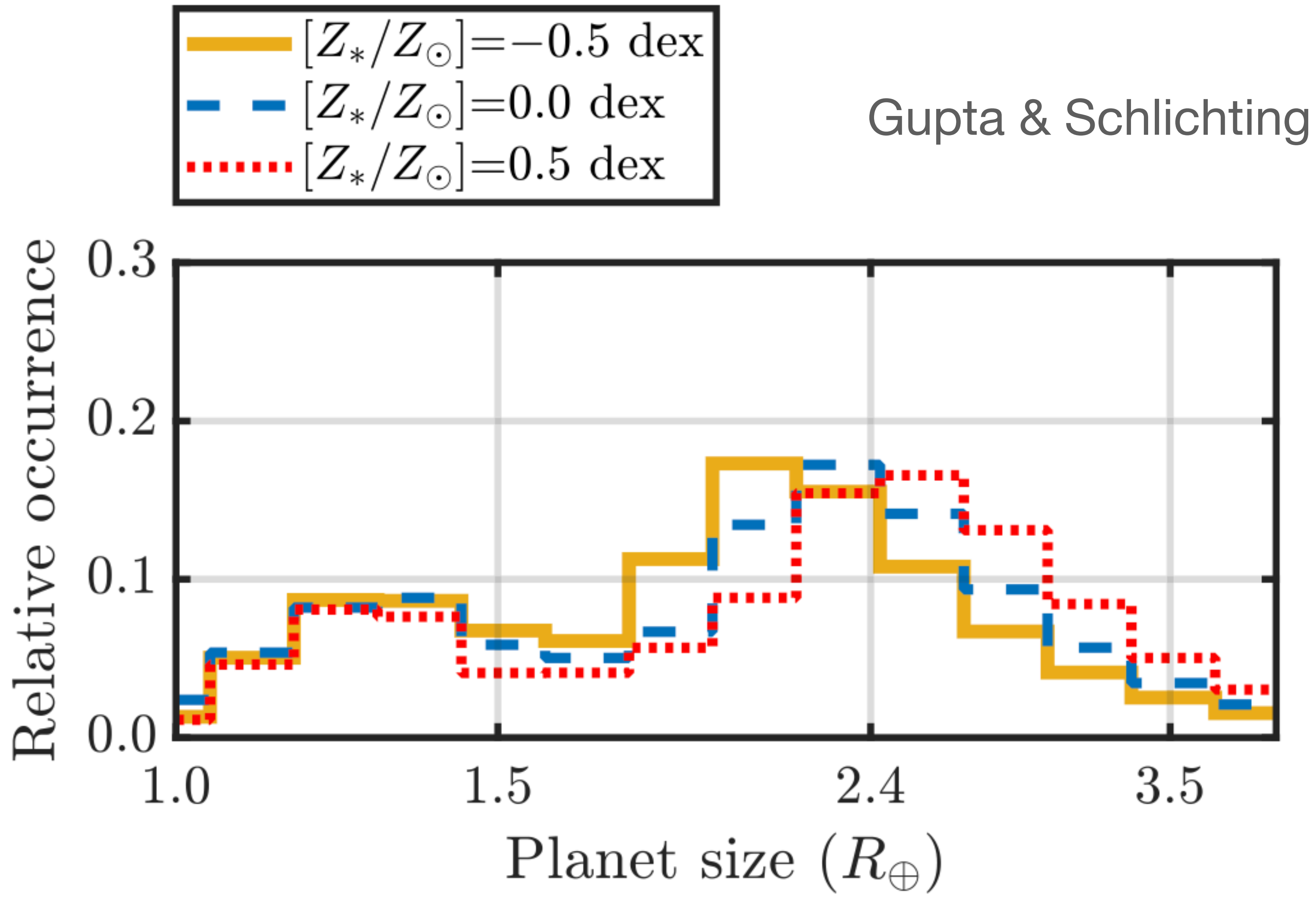
Dependence on metallicity

- In core-powered mass loss model, a planet around a metal-poor star has lower atmospheric opacity and thus loses its energy on a shorter timescale

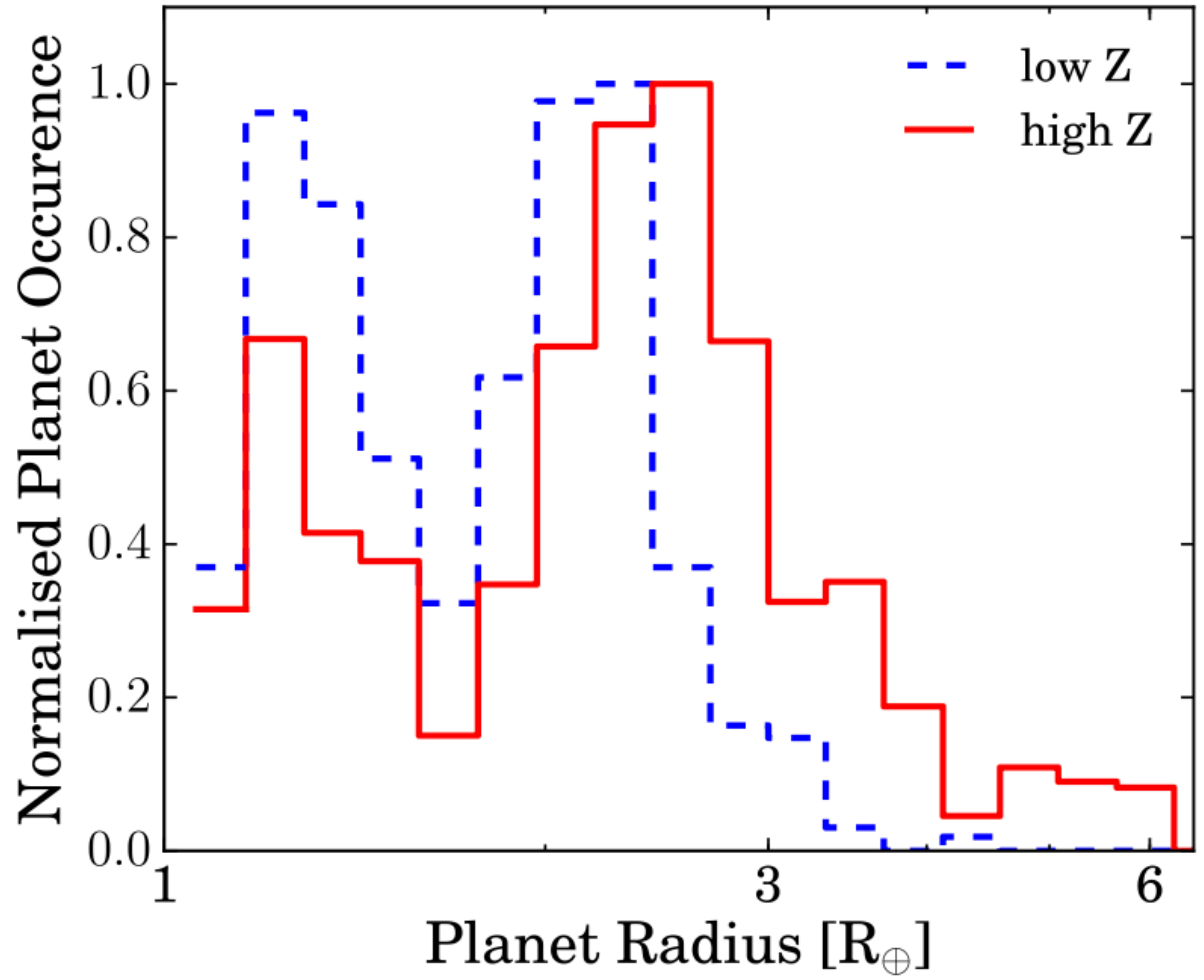
  —> sub-Neptunes will be larger around higher metallicity stars (at a fixed age)



Hirano+2018



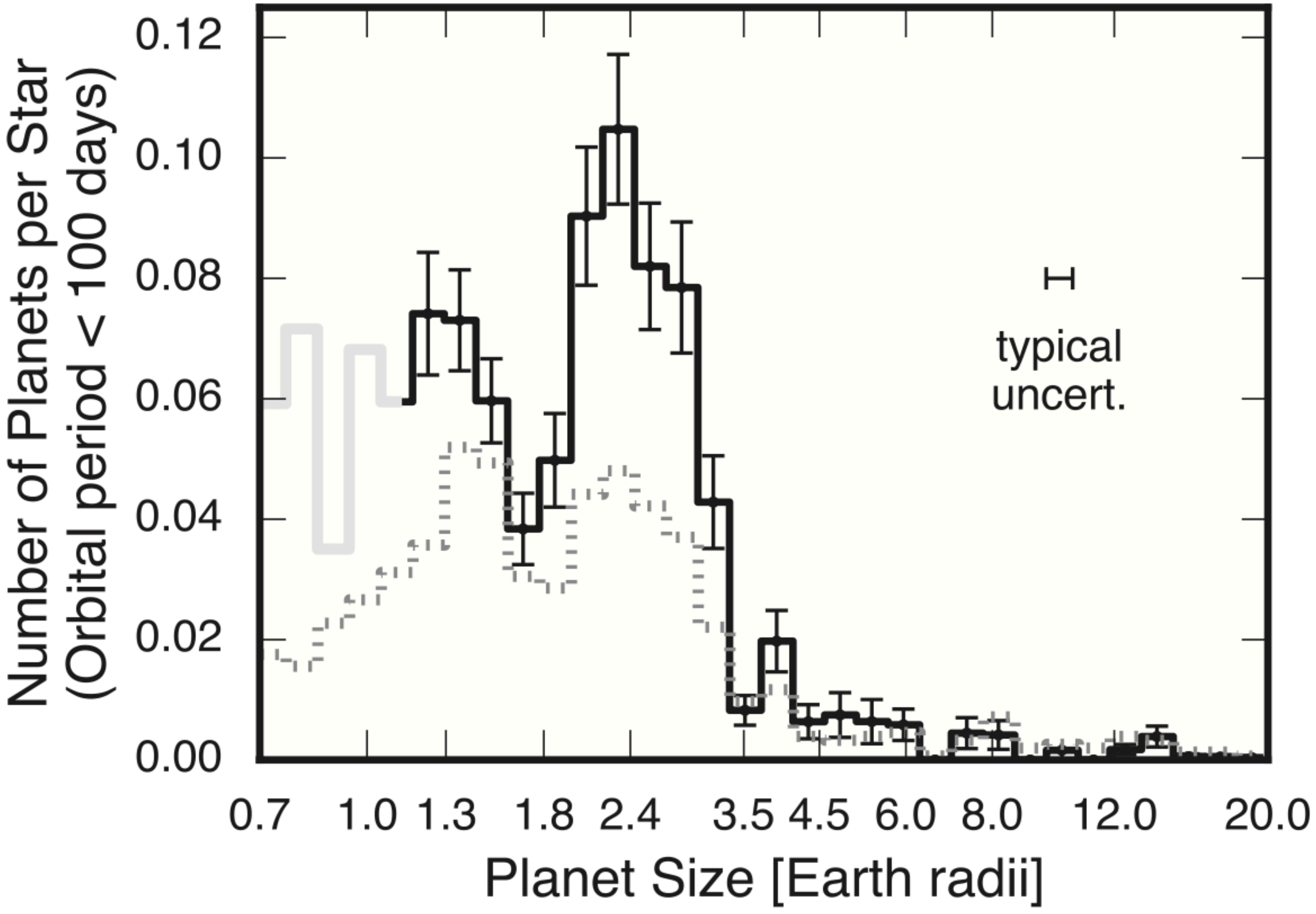
Gupta & Schlichting 2020



Owen & Murray-Clay 2018

Planets in the gap

- Planet radius measurements with ~5% precision
- The gap is not completely devoid of planets
- Consistent with core-powered mass loss due to its Gyr timescale
- Intrinsic spread of the two populations ?



Fulton & Petigura 2018

Summary

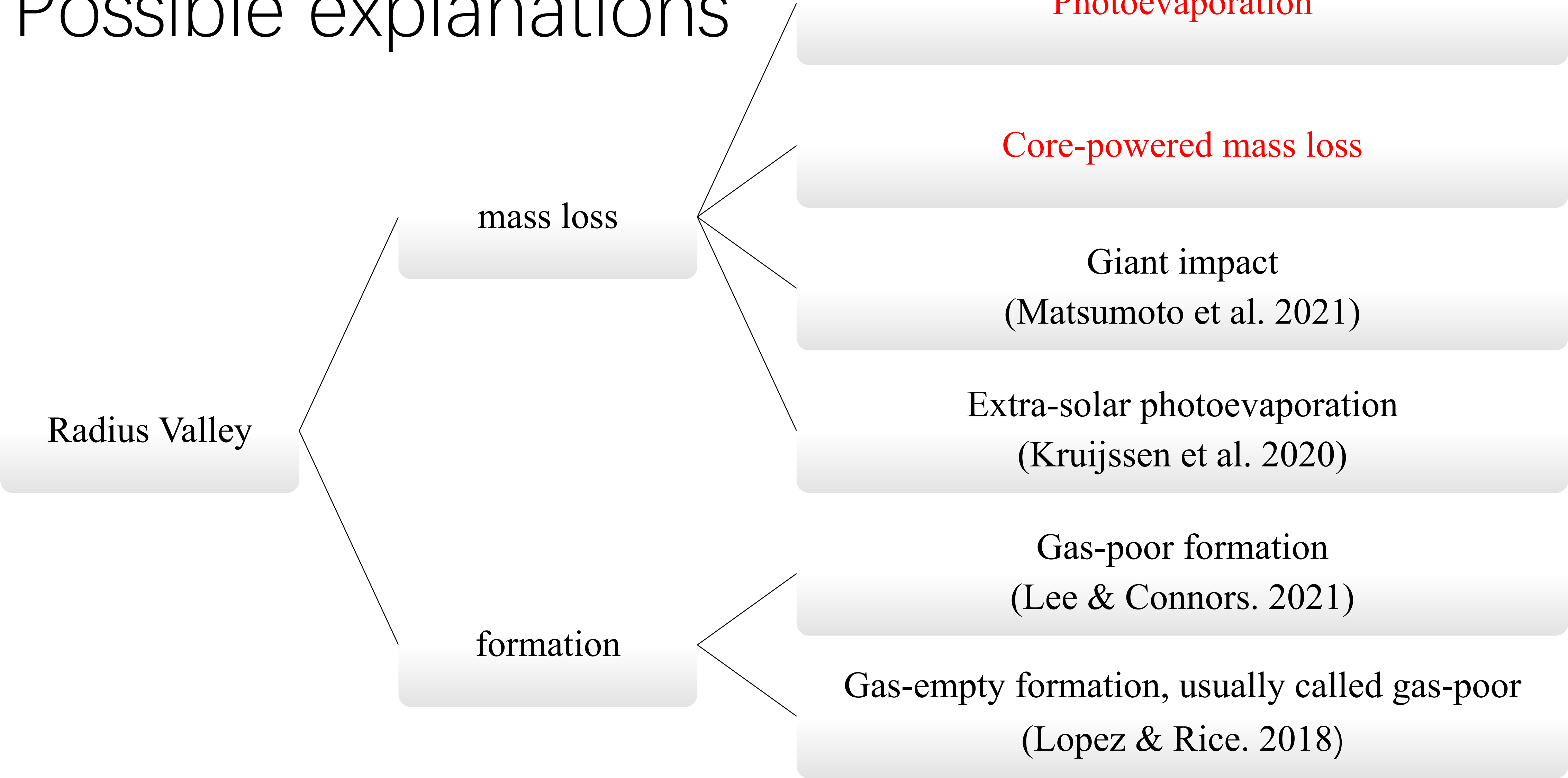
- Core-powered mass loss has relatively strong observation support, while photoevaporation needs more observations of young planets to be better examined.
- We need more planets observations
  - planets around stars with ages of ~ 100 Myr
  - planets around stars of different types

How close-in small planets around different type of stars evolve in their lifetime

Part4: Alternative explanations for radius-valley

刘肇宁 Liu Zhaoning

Possible explanations



Radius Valley

mass loss

Photoevaporation

Core-powered mass loss

Giant impact
(Matsumoto et al. 2021)

Extra-solar photoevaporation
(Kruijssen et al. 2020)

formation

Gas-poor formation
(Lee & Connors. 2021)

Gas-empty formation, usually called gas-poor
(Lopez & Rice. 2018)

Impact erosion model

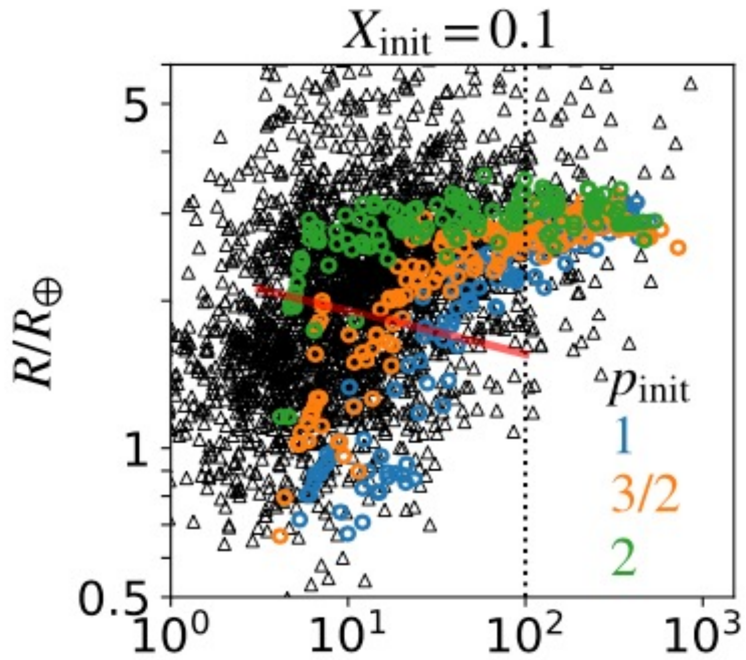
- Setting up solid surface density distribution of cores and envelop fractions

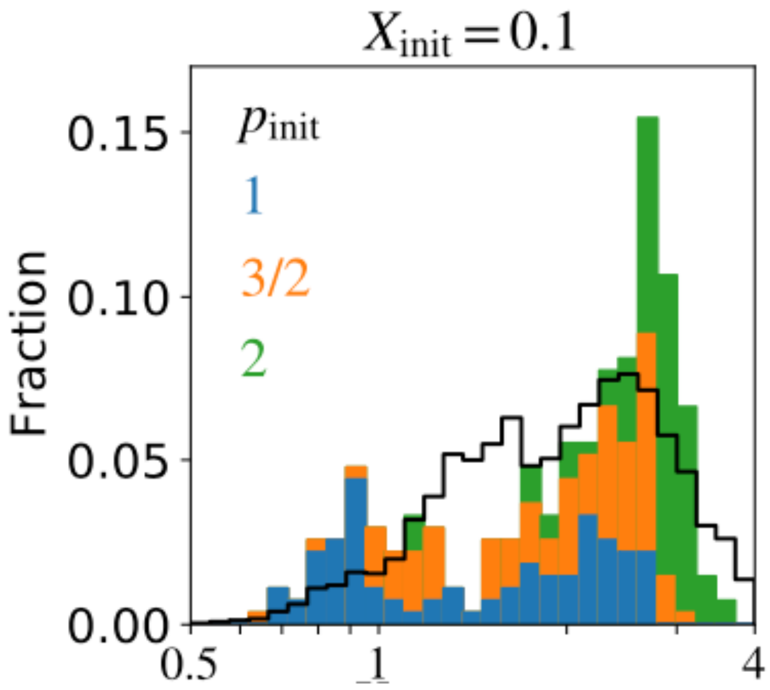
$$\Sigma = \Sigma_1 \left(\frac{a}{1\ \mathrm{au}}\right)^{-P_{\mathrm{init}}} \qquad X_{\mathrm{init}} = X_{\mathrm{env}}/M_{\mathrm{c}}$$

- N-body simulation for envelope mass loss by giant impact shock waves

- Photoevaporation

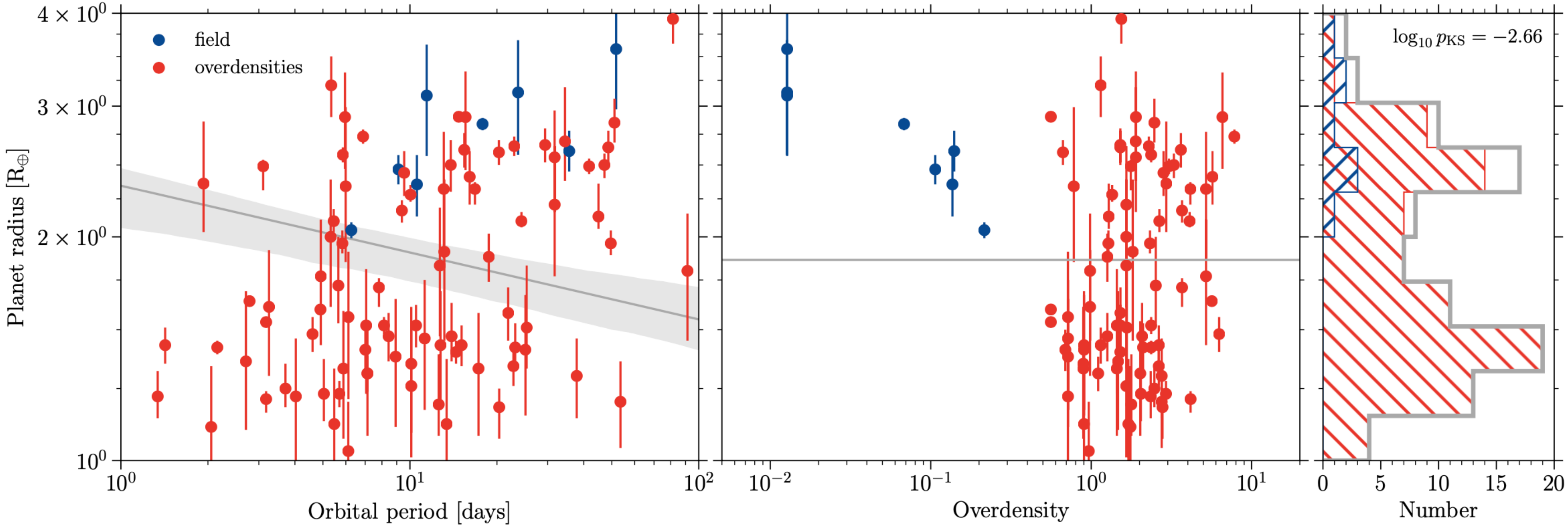
$$\dot{M}_{\mathrm{XUV}} = \epsilon_{\mathrm{PE}} \frac{\pi R_{\mathrm{p}}^3 L_{\mathrm{XUV}}}{4\pi a^2 G M_{\mathrm{p}} K_{\mathrm{tide}}}$$





Extra-solar photo-evaporation model

Sub-neptunes appears only in the low star density environment.



Kruijssen et al. 2018

Gas-poor formation model

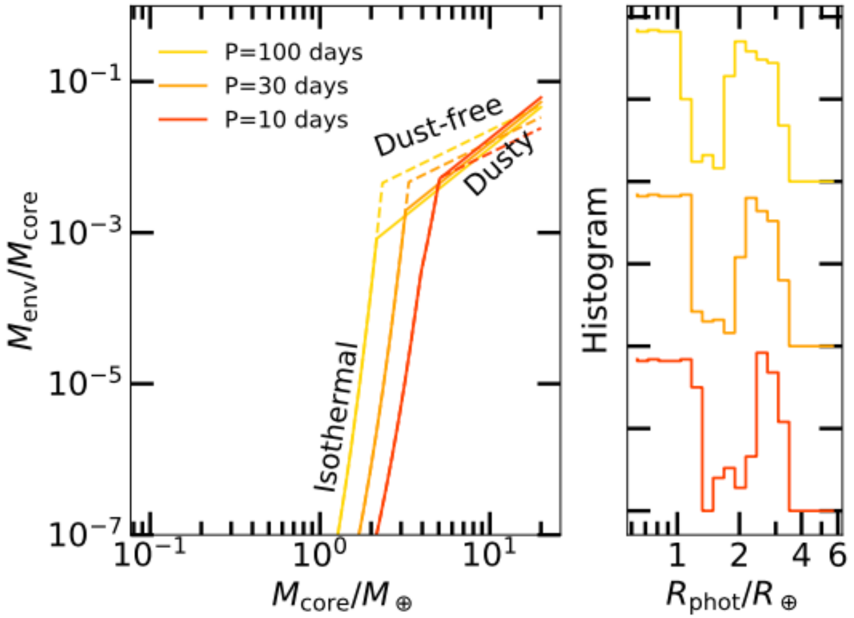
- Motivation:

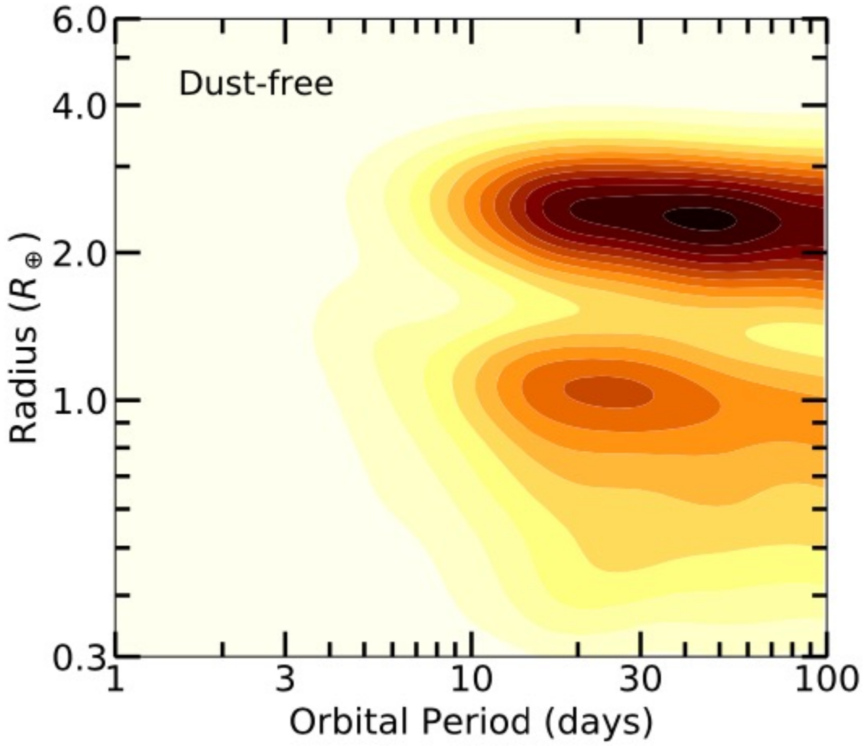
The photo-evaporation requires a planet mass peak at $\sim 4M_*$, which conflicts with the RV follow-up of Kepler planets.

- Gas-poor environment:

A gas-poor environment is deemed favorable for preventing runaway gas accretion. The mass of planets' fully isothermal envelopes are limited by

$$M_{\rm iso} = 4\pi\rho_{\rm disk}\int_{R_{\rm core}}^{R_{\rm out}} r^2 {\rm Exp}\left[\frac{GM_{\rm core}}{c_{s,\rm disk}^2}\left(\frac{1}{r}-\frac{1}{R_{\rm out}}\right)\right] dr$$





Gas-empty formation theory

- If these planets took 10 Myr to finish assembling, their proto-planetary gas discs would have already dissipated by that point. The rocky and non-rocky exoplanets are two separate populations originating from different formation timescales.

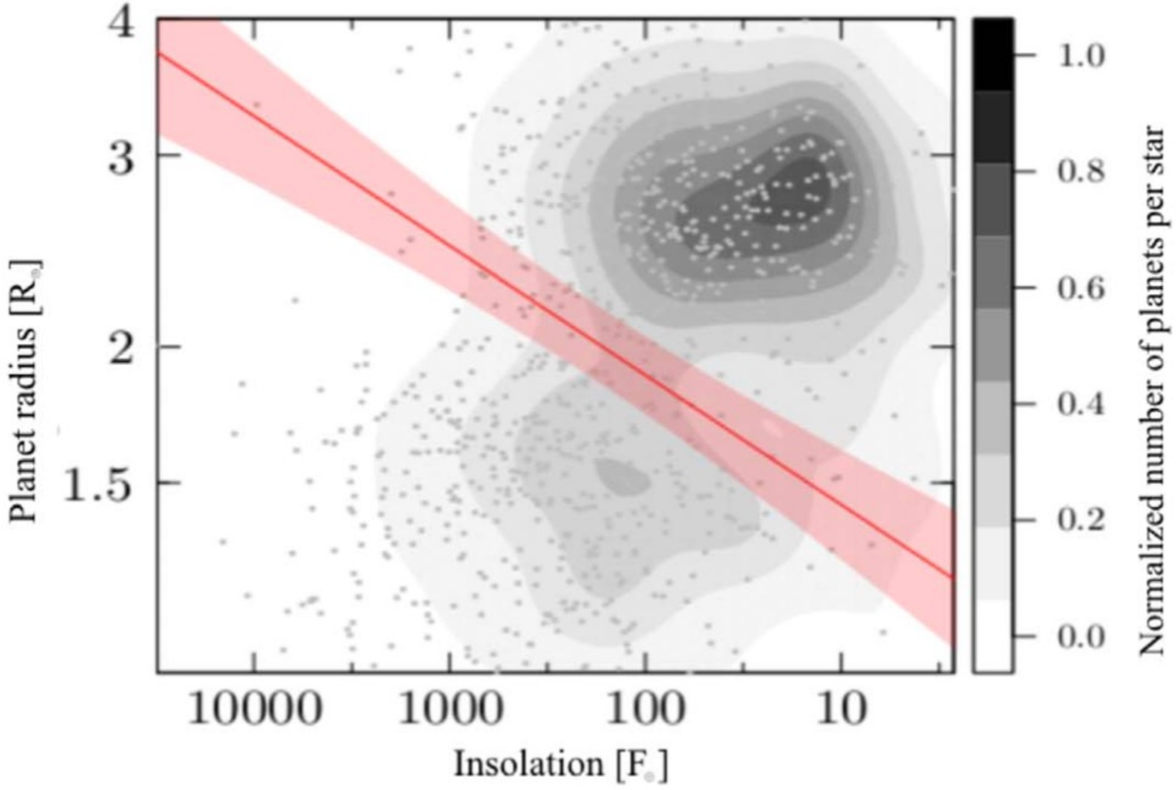
- The maximum size of rocky planets is determined by the available supply of solid materials that a planetary core can accrete by collisions.

$$\mathrm{M}_{p,max} \propto \Sigma \times r_{\mathrm{H}} \propto a^{0.6} M_s^{-0.5} \qquad \mathrm{R}_{\mathrm{trans}} \propto a^{0.16} M_s^{-0.14}$$

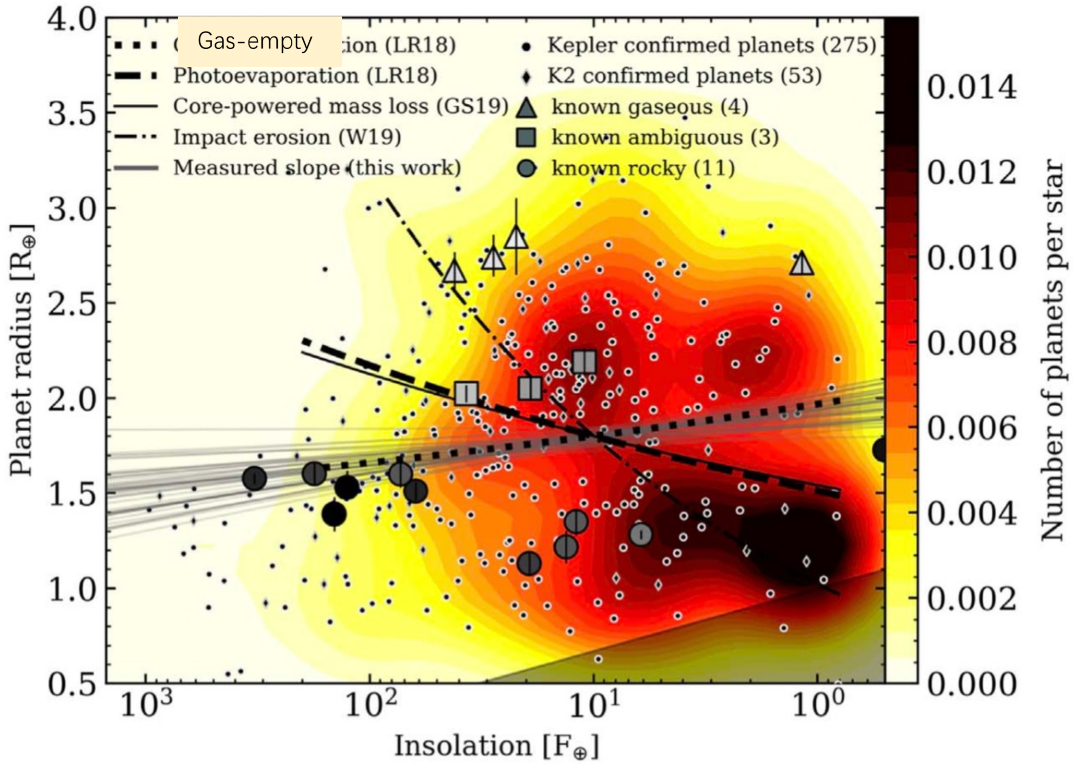
	Photo-evaporation	Core-powered	Impact erosion	Gas-empty formation
$d \log R_p / d \log F$	0.11	0.10	0.05	-0.08

Gas-empty formation theory

M-dwarf Stars Observation



Cloutier & Menou. 2020



Cloutier & Menou. 2020

Gas-empty formation theory

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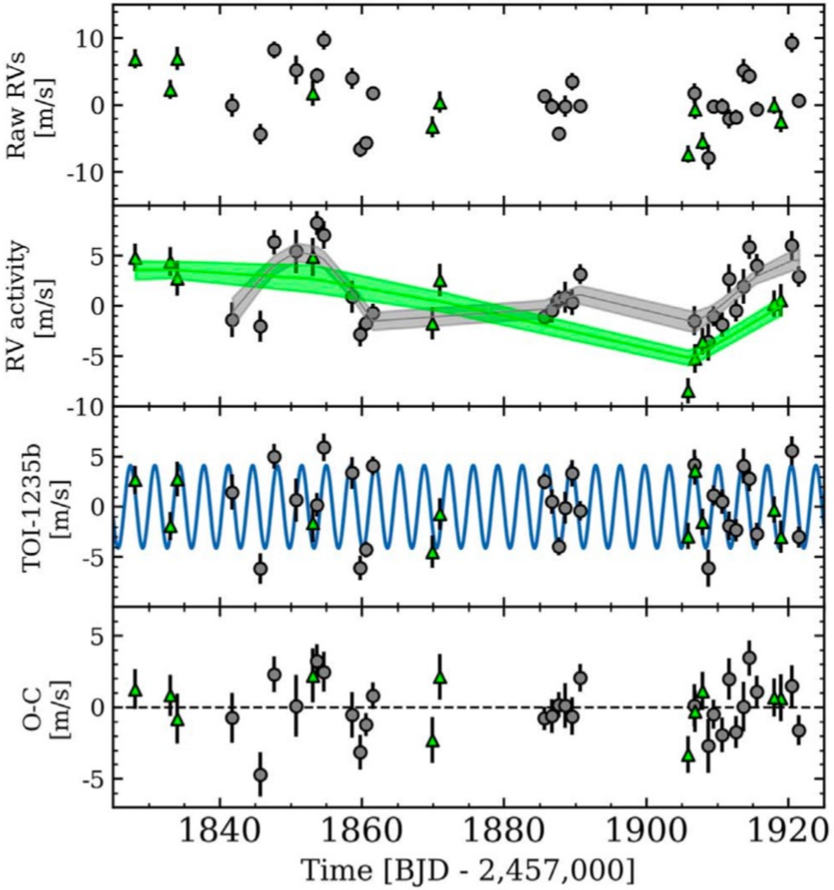
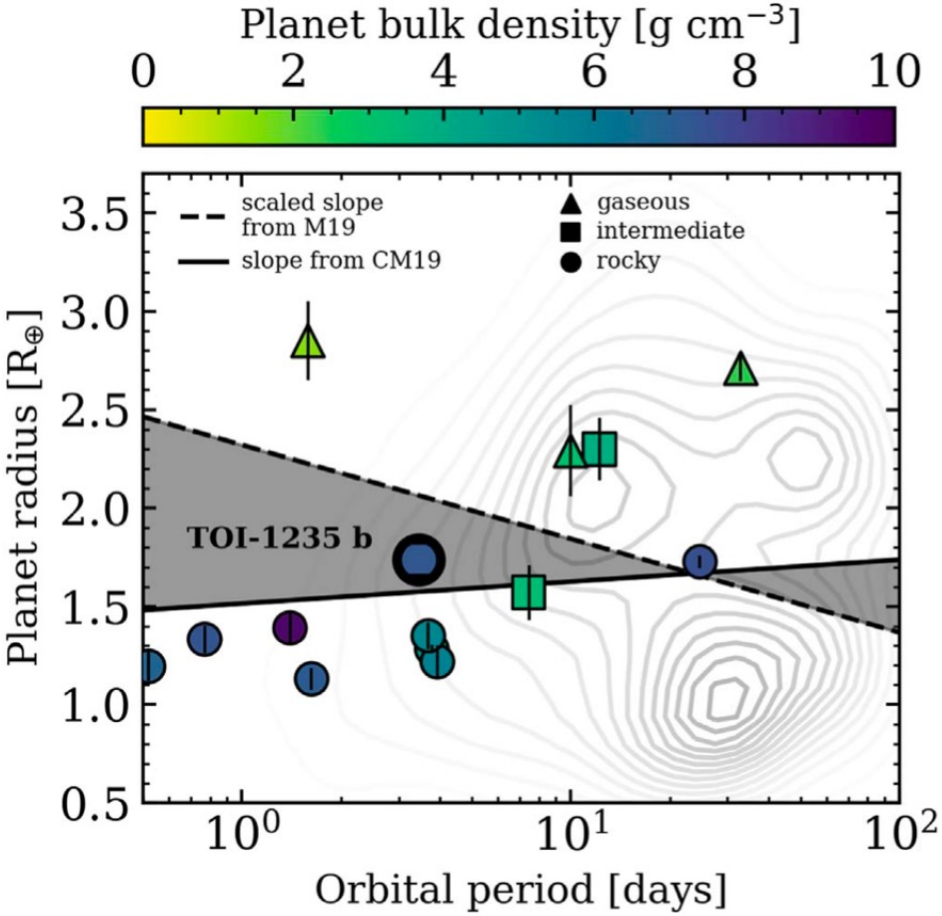


Cloutier et al. 2020



Cloutier et al. 2020

Need for multi-physics scenario

	Photo-evaporation mass loss	Core-powered mass loss	Impact erosion mass loss	Extra-solar photo-evaporation	Gas-poor formation	Gas-empty formation
Orbit period	✅	✅	✅❓	❌	✅	❌❓
Stellar mass	✅	✅	❓	❓	✅	❌
Stellar age	❌❓	✅❓	❓	✅❓	❓	❌
Phase-space density	❌	❌	❌	✅	❌	❌

Summary

- There are many alternative explanations for radius valley, other than the photo-evaporation and core-powered mass loss model.

- Models like the gas-empty formation model doesn’t work in the sun-like stars, but the scenario may contribute in the very low-mass stars.

- There is more or less inconsistency between the observations and each individual model. Multi-physics model is needed for future research.