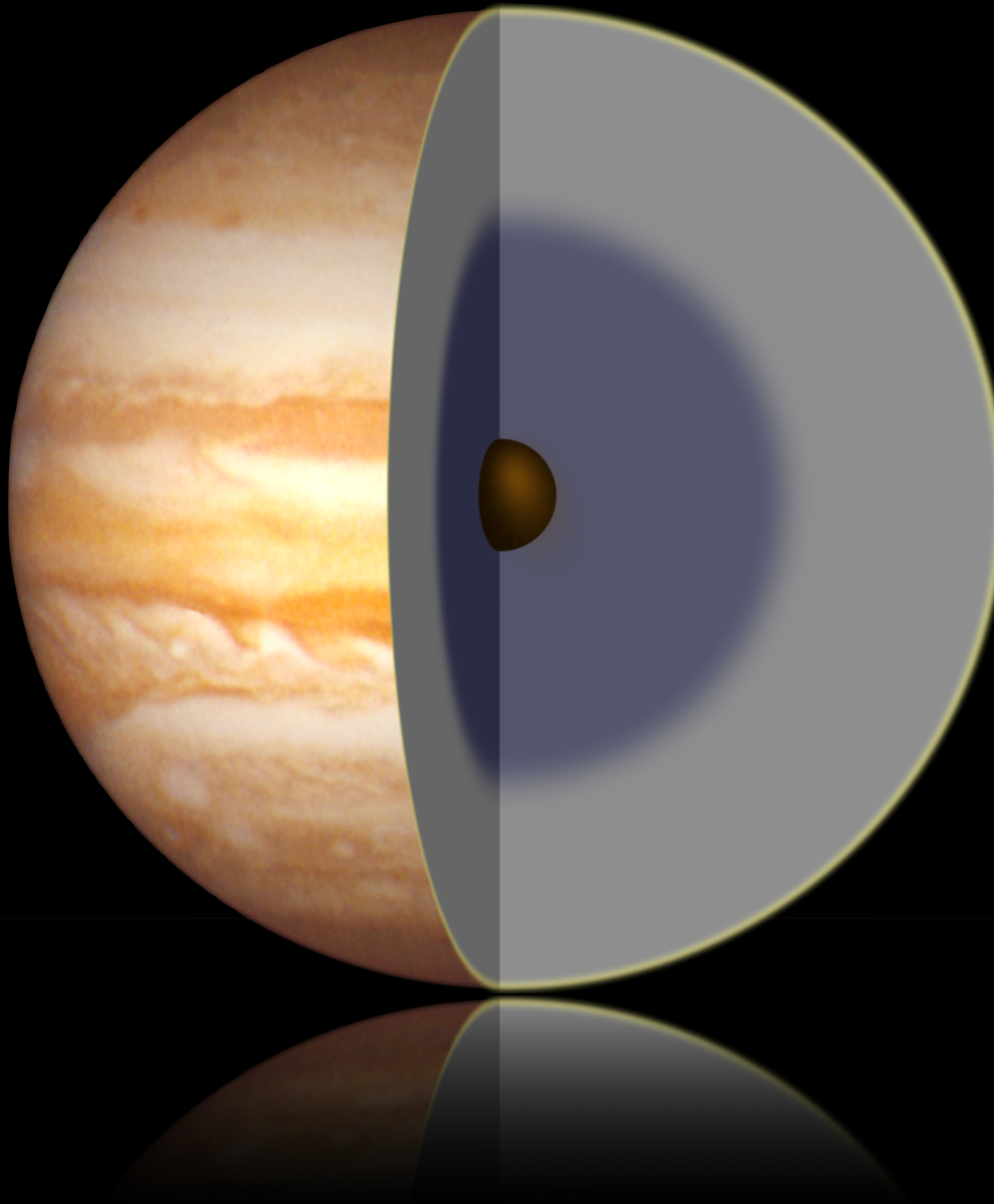
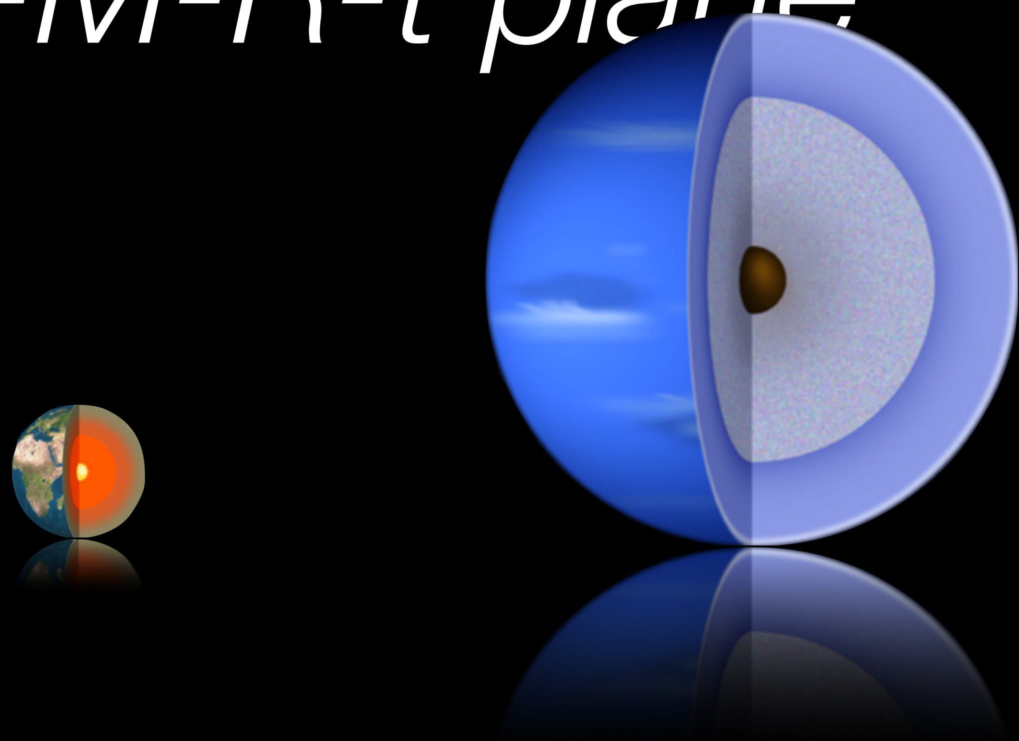
CHEOPS Meeting Madrid 18.6.2015

Breaking the compositional degeneracy in the a-M-R-t plane





Christoph Mordasini

Y. Alibert, W. Benz, K. Dittkrist, P. Molliere, S. Jin, G. Marleau

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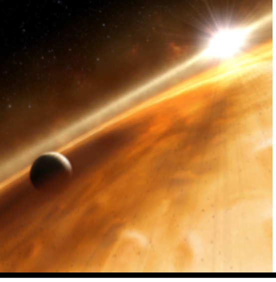
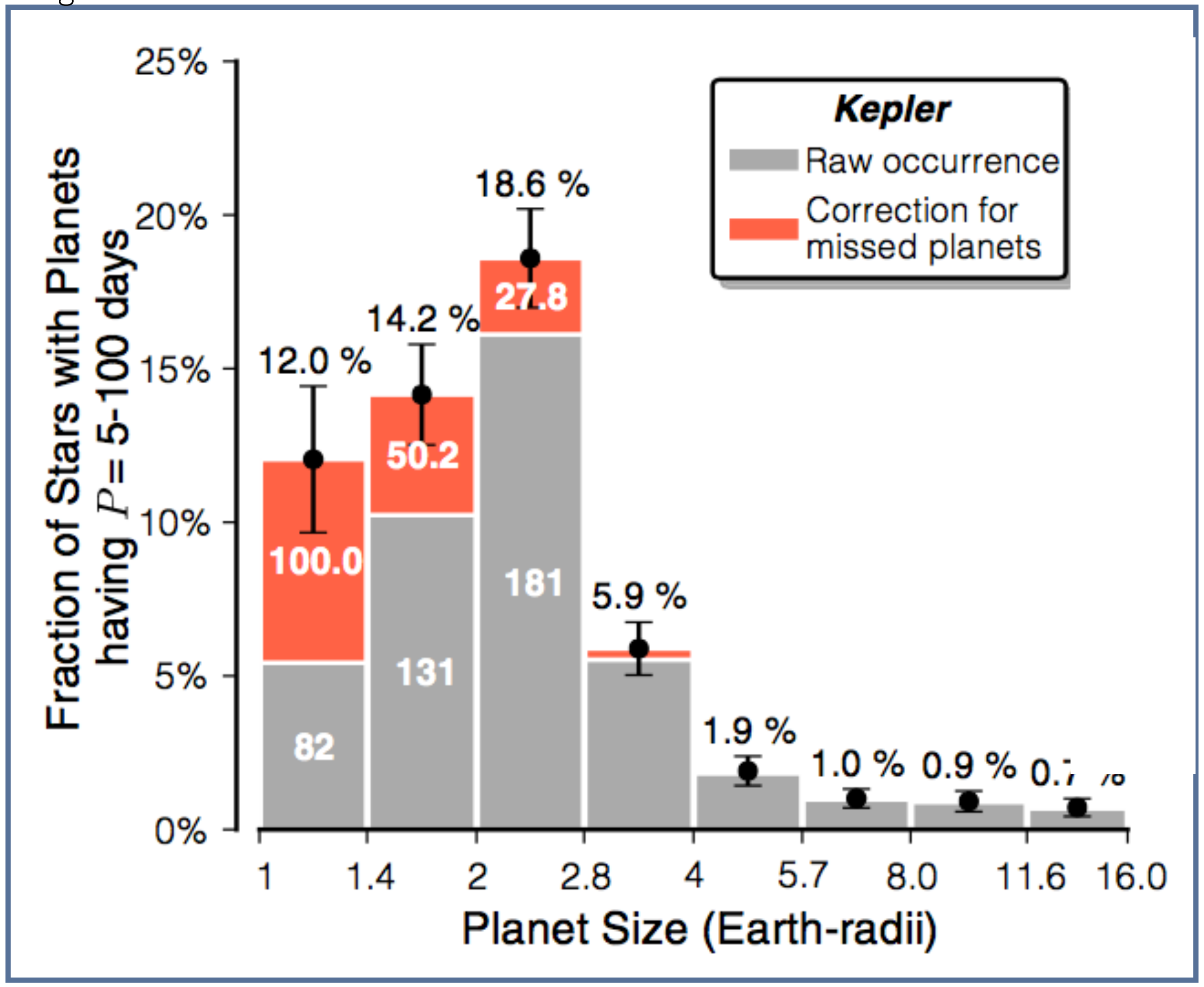
FNSNF

PlanetS

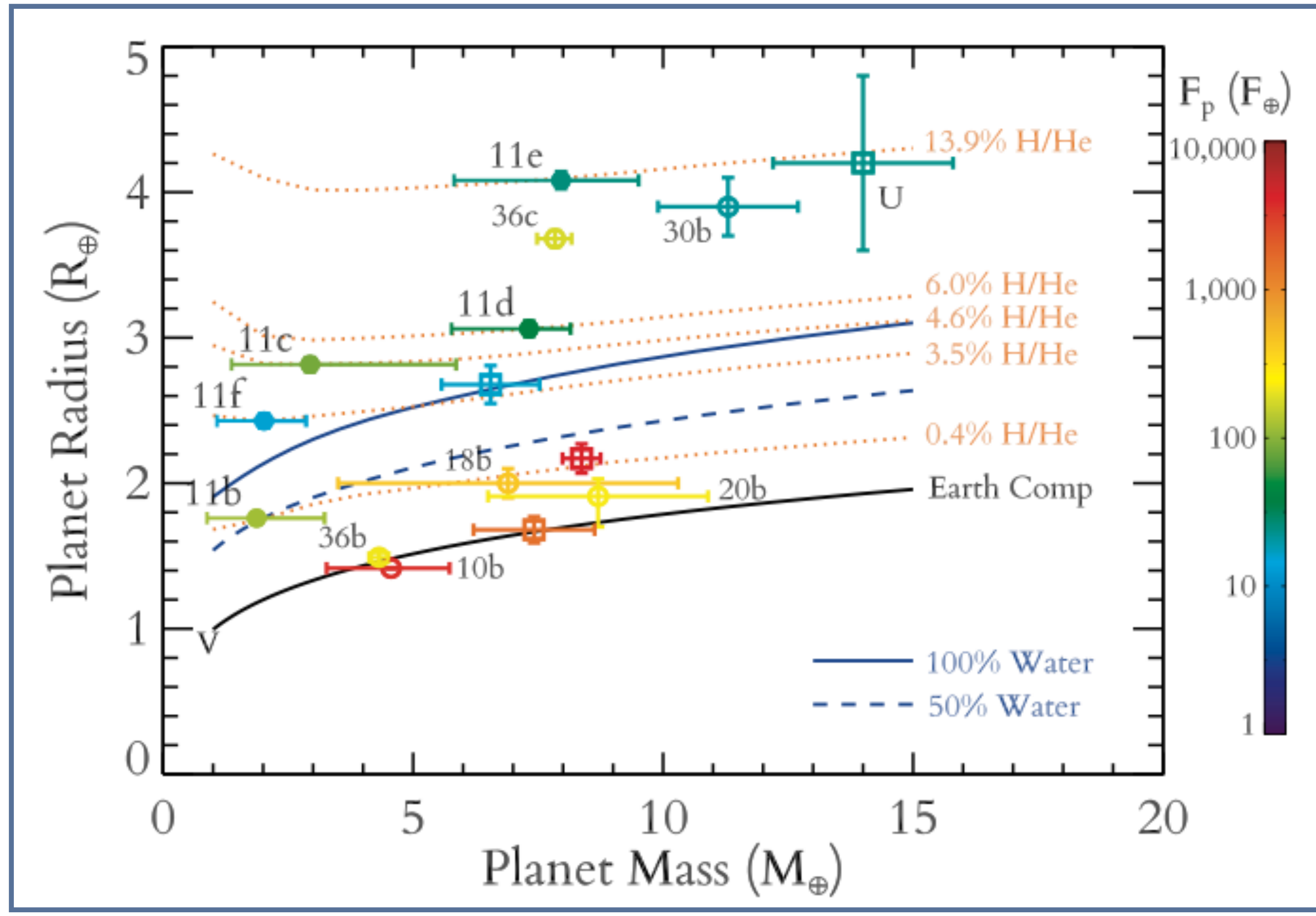


Close-in low-mass planets

Petigura et al. 2013

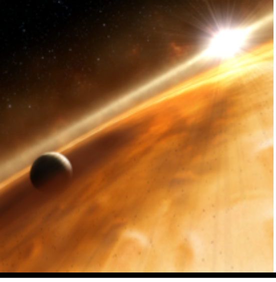


Lissauer et al. 2013



- Very frequent: ~50% of solar like star ($1<R/R_\oplus<4$ & P<100 days; Kepler)
- From RV: ~40% with $M<30\ M_\oplus$ inside 50 days (HARPS)
- Large diversity in composition. Some w. low density (H/He envelopes of ~1-10% for $R/R_\oplus > 1.6$), some Earth-like

Formation mechanism?



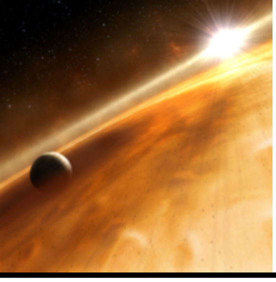
Formation mechanism?

	Strictly in situ	Migration then final assembly	Large scale migration after assembly from a>a
Core composition	Rocky	Rocky - Icy potentially radial composition gradient	Icy
Primordial H/He (post-formation)	Yes (w/o isolation) No (w isolation)	Yes (w/o isolation) No (w isolation)	Yes

Knowing the bulk composition (H/He; rocky, icy, mixed) would be of very high interest for formation theory

Formation beyond iceline: ice mass fraction 50-75%

Hansen & Murray 2012, 2013, Chiang & Laughlin 2013, Raymond & Cossou 2013, Ida & Lin 2013, Lee et al. 2014, Schlichting 2014, Hands et al. 2014, Cossou et al. 2014, Chattarjee & Tan 2014, Ohigara et al. 2015, Inamdar & Schlichting 2015, ….

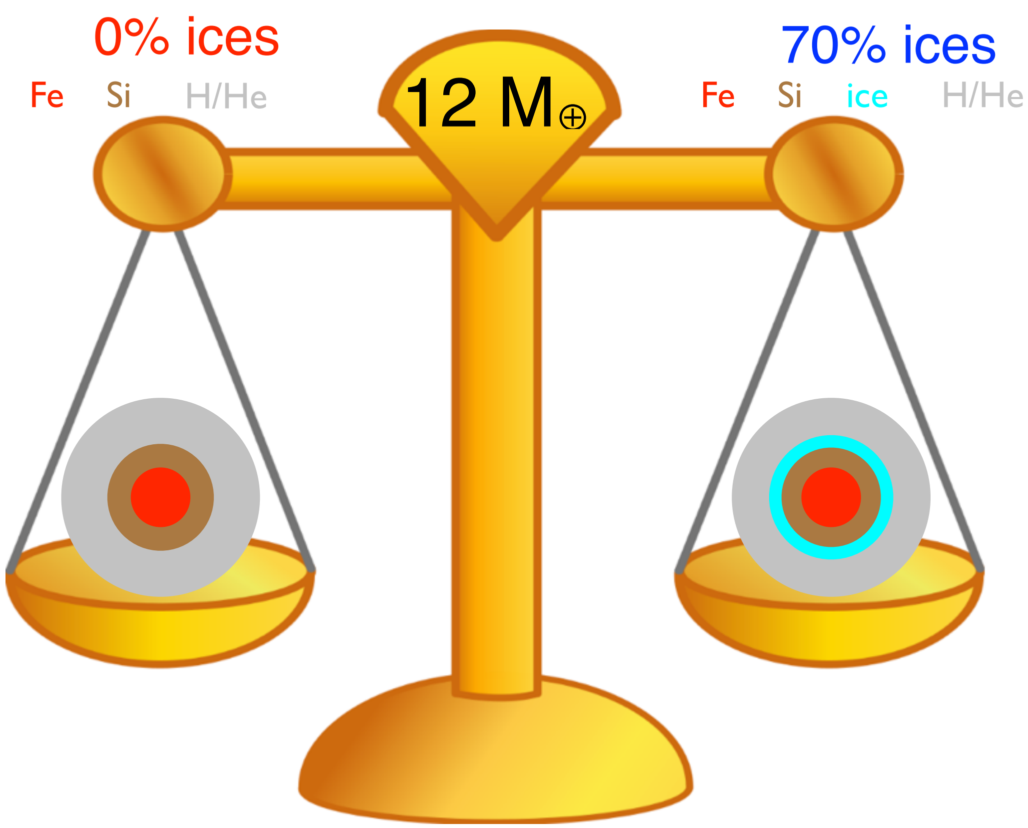


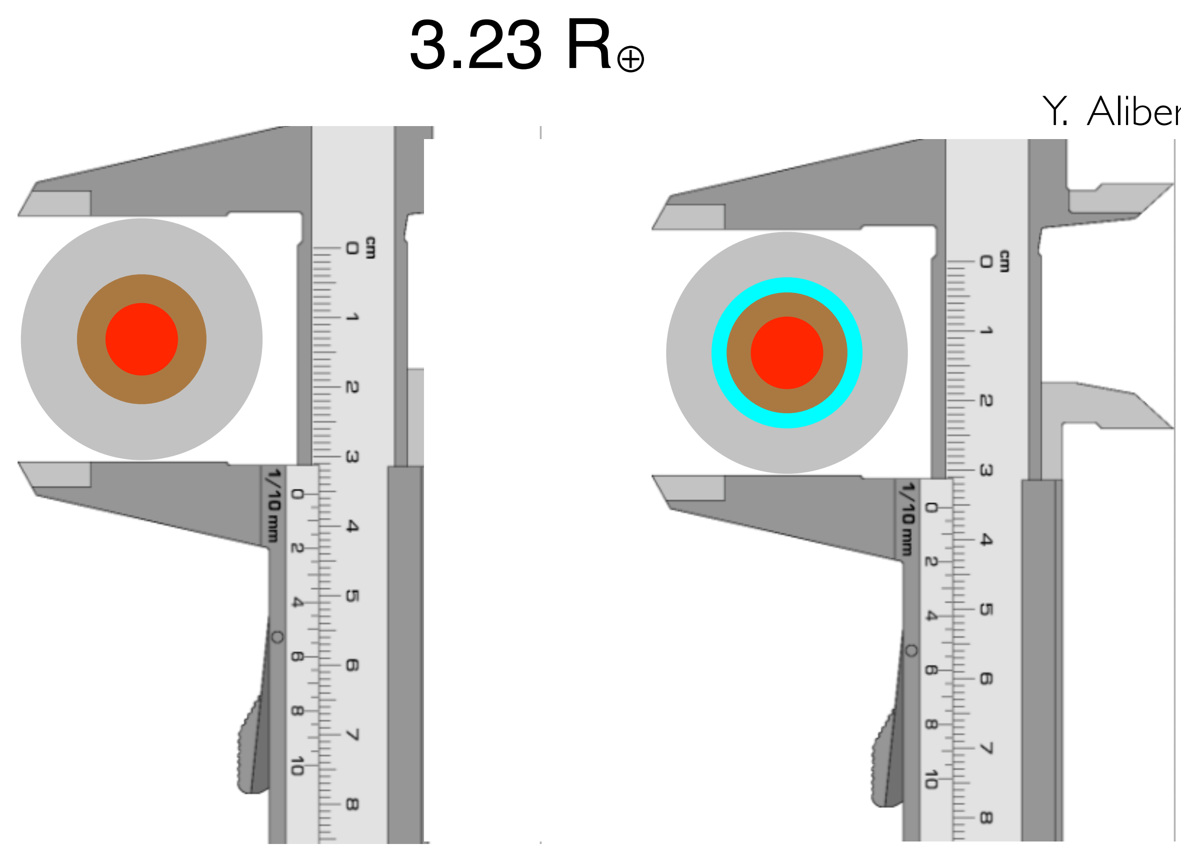
Degenerate M-R relation

Formation of close-in low-mass planets: in situ vs. migration
Formation beyond iceline: ice mass fraction 50-75%

Knowing the bulk composition (H/He; rocky, icy, mixed) would be of very high interest for formation theory

Even for only the 4 standard “ingredients” of planetary interiors (iron, silicates, ices, H/He) the M-R is degenerate:

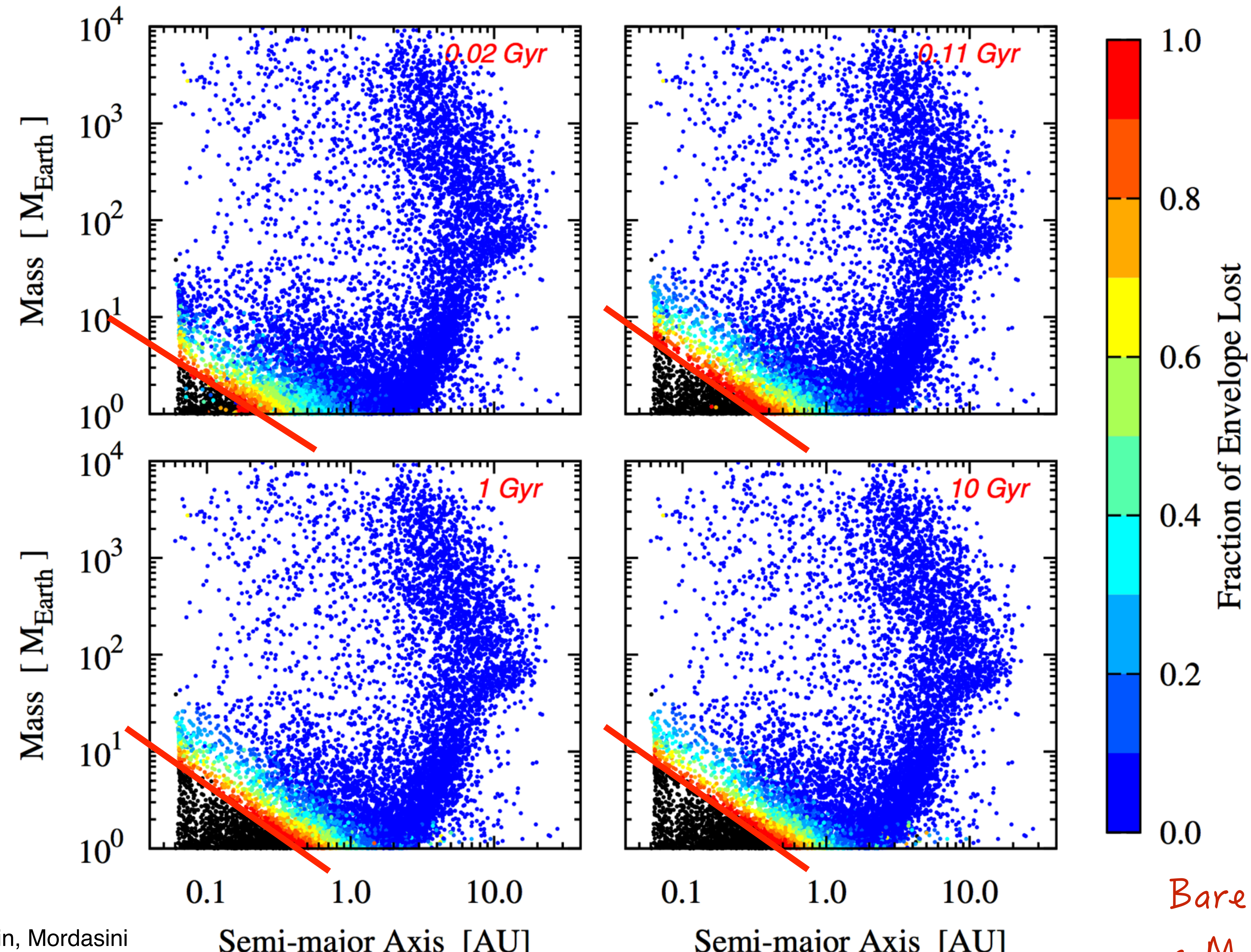




⇒reduce the number of unknown “ingredients” to 2 for some planets

H/He: Evolution with atmo. escape

M_{star}=1 M_{sun} Isothermal Type I rate x 0.1. Cold accretion. 1 embryo/disk, f_{opa}=0.003



Jin, Mordasini et al. 2014

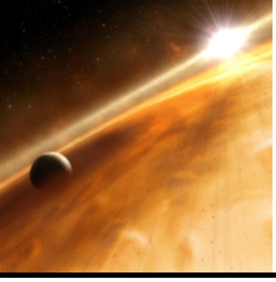
Bern model: Core-accretion population synthesis

Self-consistent formation and evolution (cont. & cooling) with XUV-driven atmo. escape.

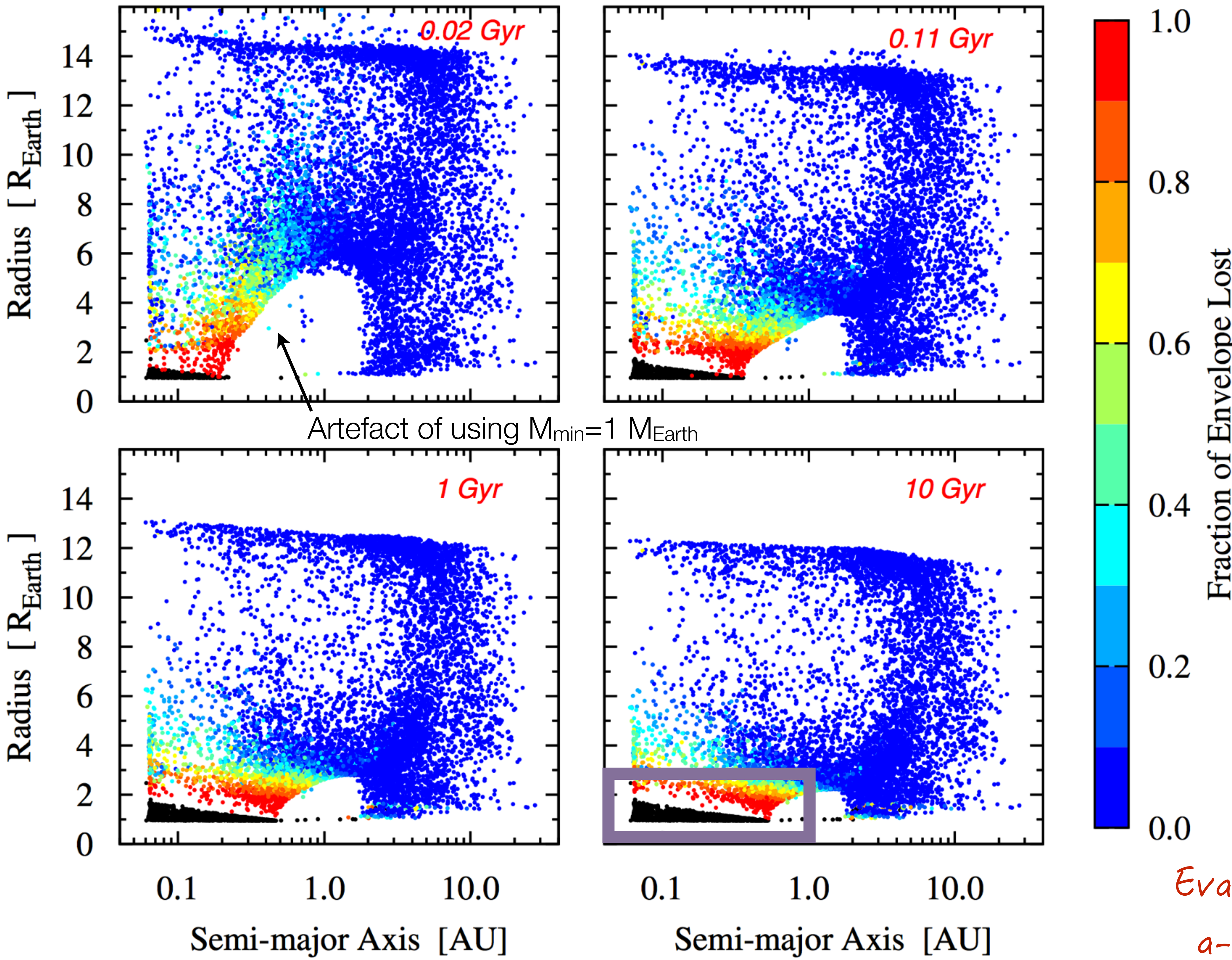
Not much evolution after >~100 Myr

Bare core triangle

a-M is hardly affected

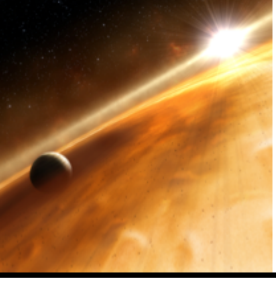


The evaporation valley



Evaporation valley
a-R is affected

cf Lammer et al. 2003, Baraffe et al. 2004, Erkaev et al. 2007, Murray-Clay et al. 2009, Lopez et al. 2013, Owen & Wu 2013

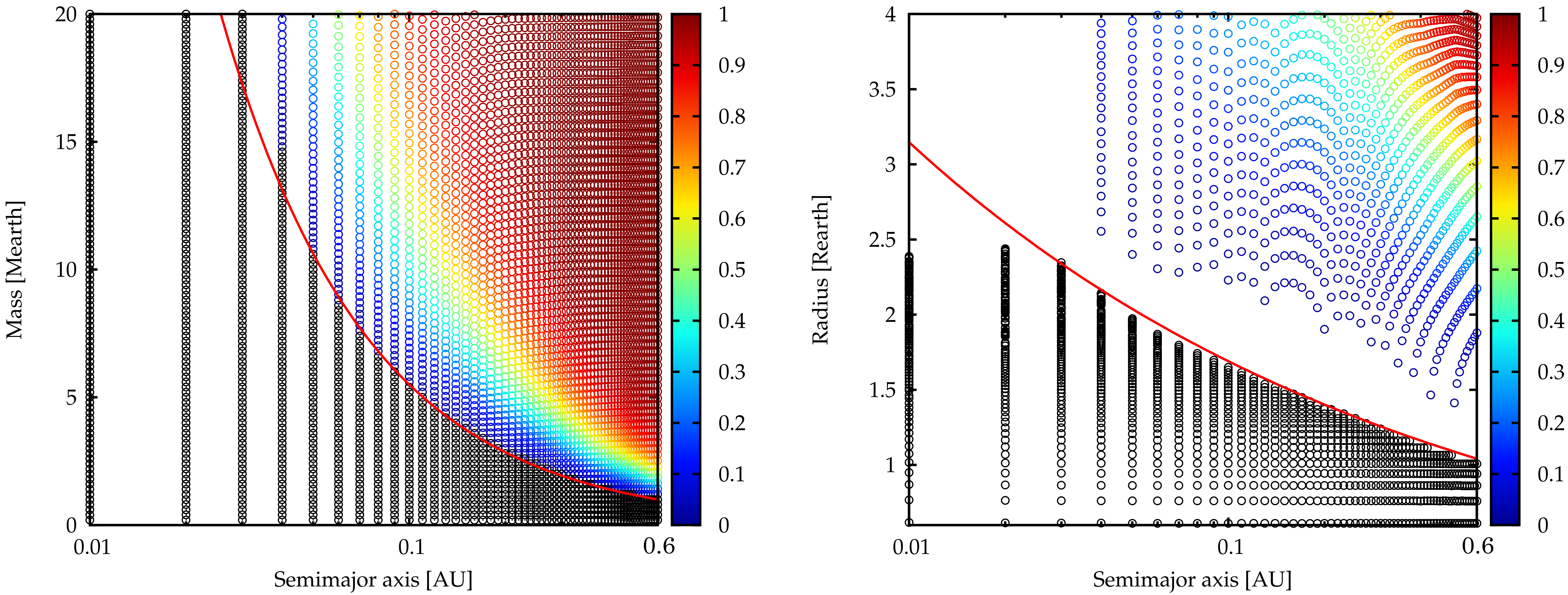


Systematic investigation

Systematic study: a=0.01-0.6 AU; M_{core}=0.2-20 M_{Earth}

Initial H/He envelope mass: $$M_{\rm enve} = 0.03 \times \left(\frac{M_{\rm core}}{M_\oplus}\right)^2 M_\oplus$$

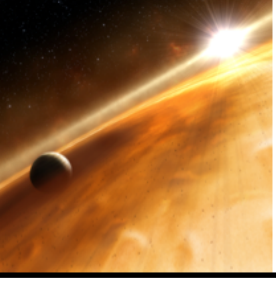
T=5 Gyrs



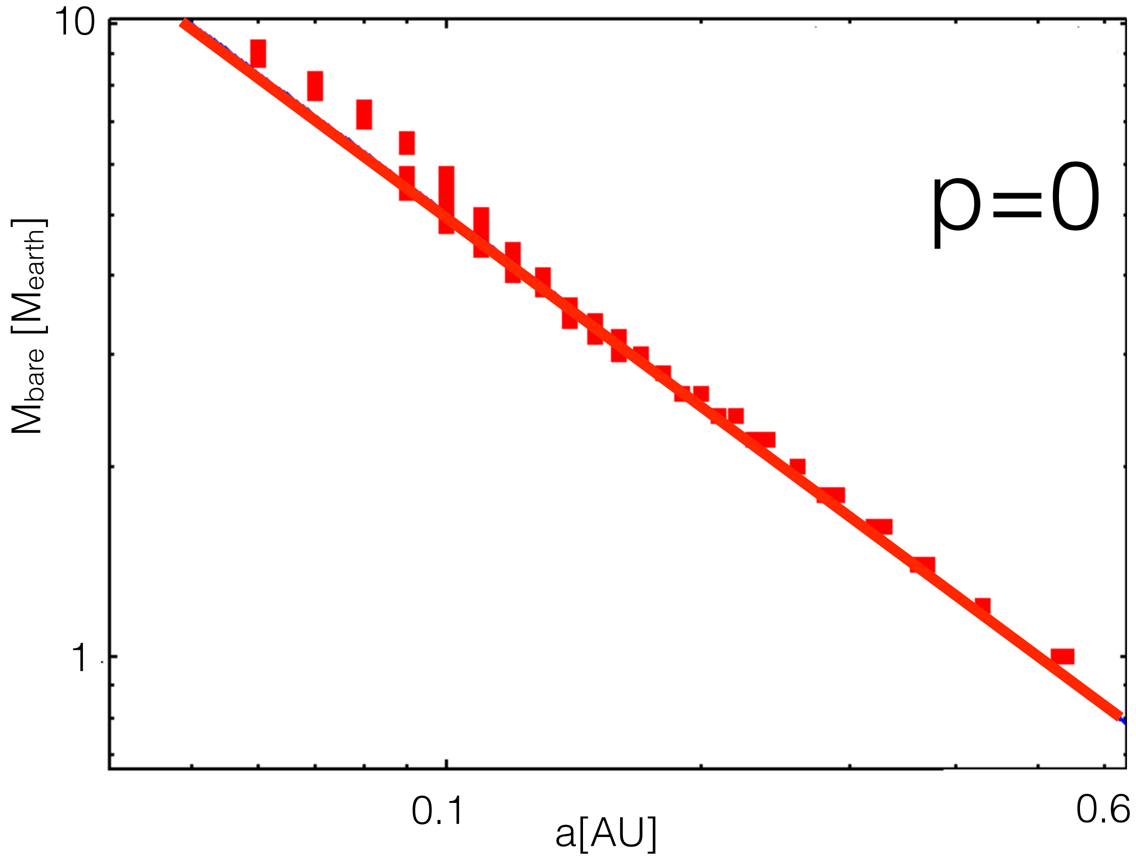
$$\frac{M_{\rm bare}}{M_\oplus} = 5.5\left(\frac{a}{0.1{\rm AU}}\right)^{-0.95}$$

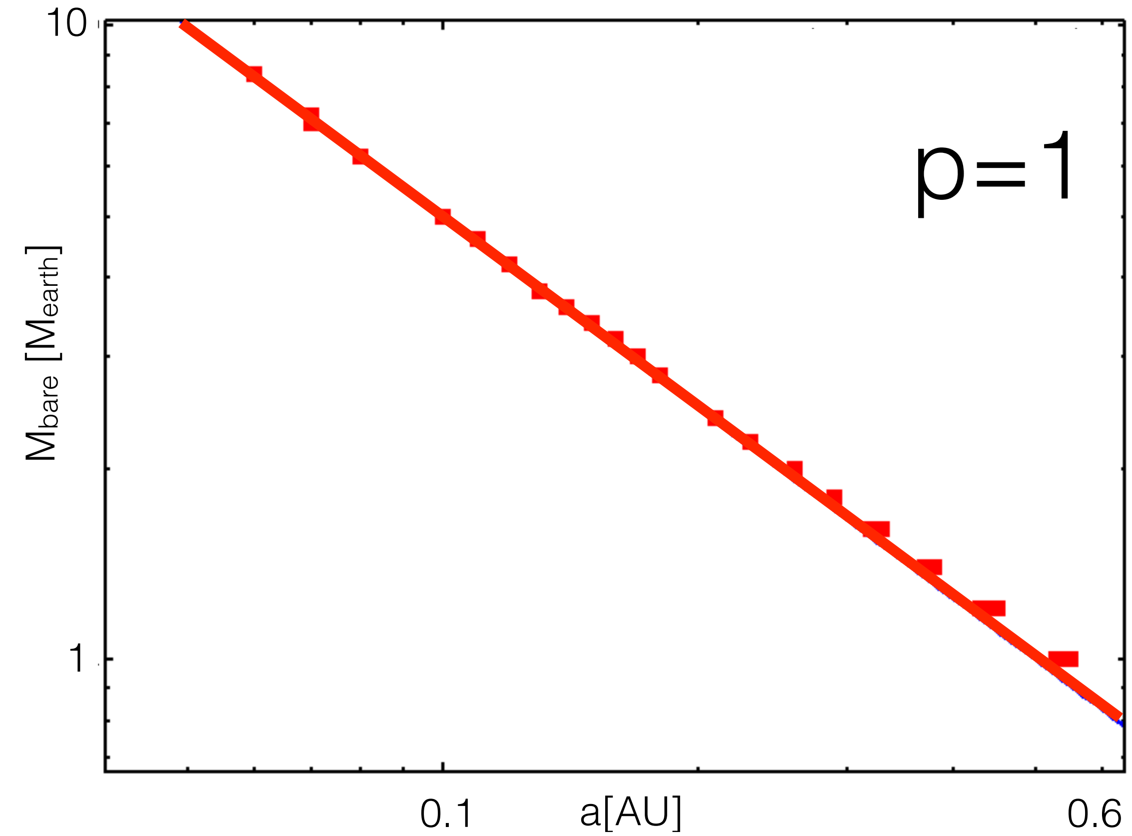
$$\frac{R_{\rm bare}}{R_\oplus} = 1.69\left(\frac{a}{0.1{\rm AU}}\right)^{-0.27}$$

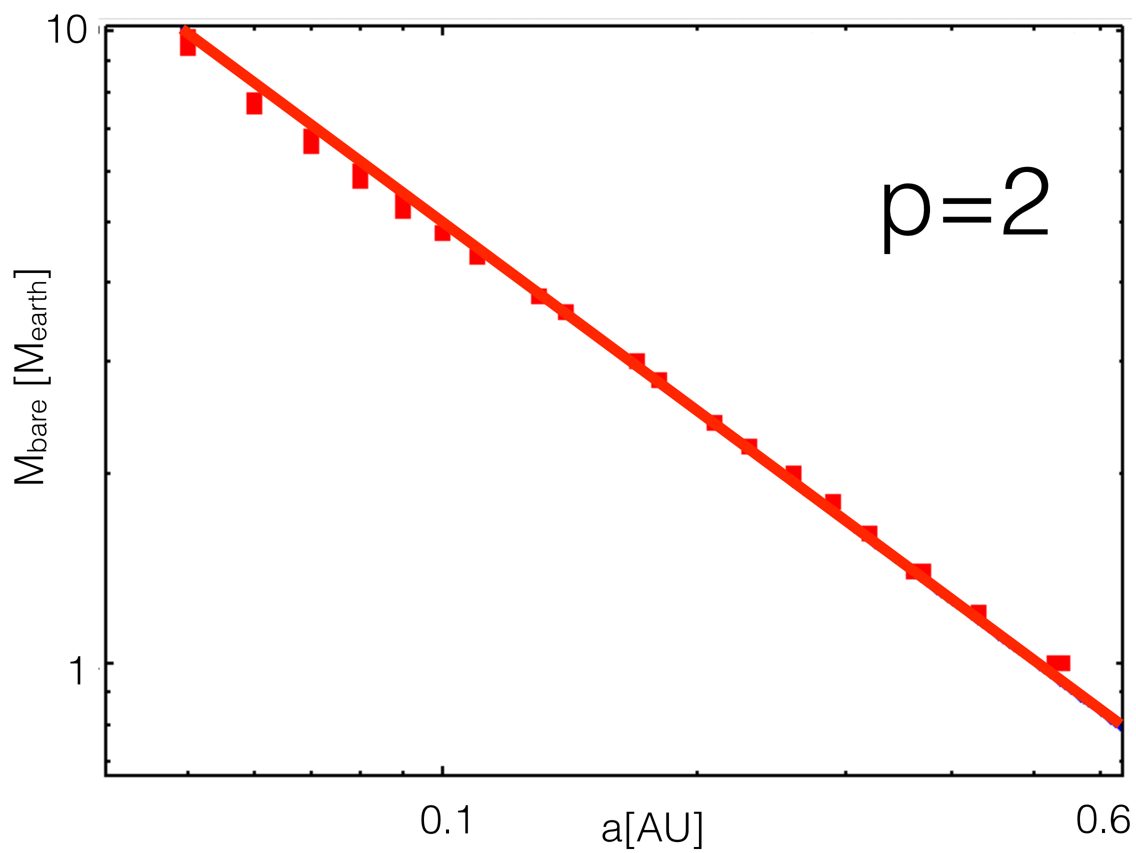
cf. Rogers 2014



The solid-gas transition



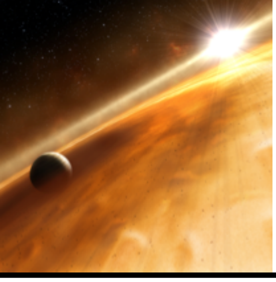




$$M_{\rm enve} = 0.03 \times \left(\frac{M_{\rm core}}{M_\oplus}\right)^p M_\oplus$$

M_{bare} independent on p

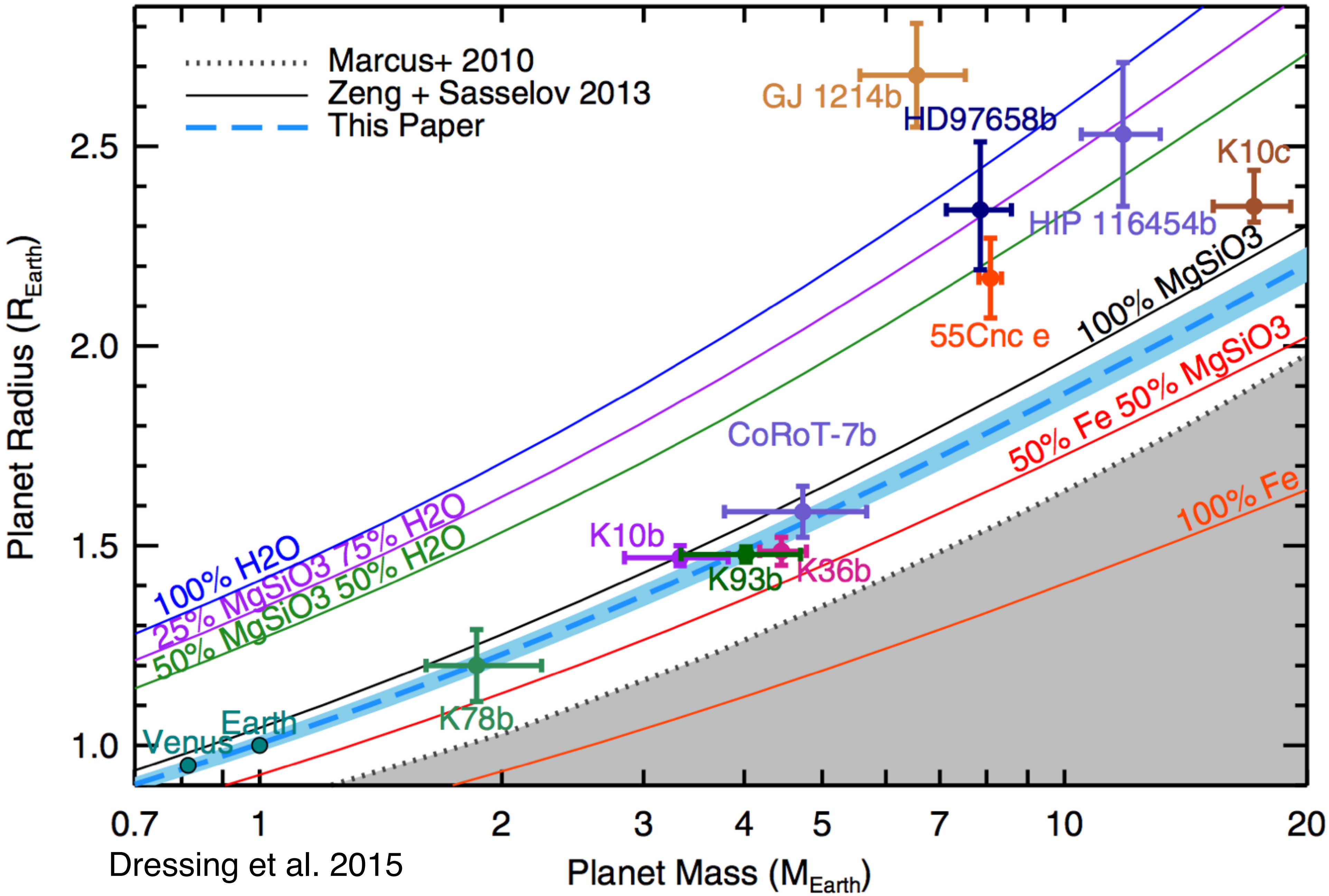
Why?



Iron mass fraction ?

Earth, Mars, Venus (but not Mercury & the Moon):
~1/3 Iron core : ~2/3 Si mantle (by mass)

Same as expected from solar composition



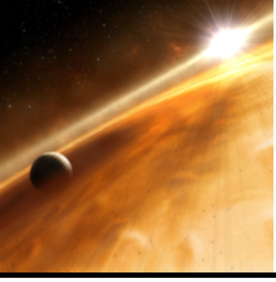
Dressing et al. 2015

Marboeuf et al. 2014

Dorn et al. 2015

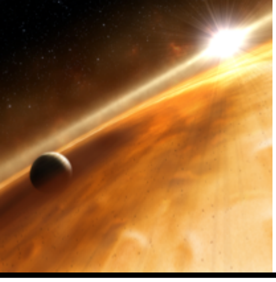
Need stellar chemical composition [Si/Fe], [Mg/Fe]

If H/He excluded (in bare core triangle), and assuming f_{Iron}=1/3 is universal, we can calculate the ice mass fraction from M and R

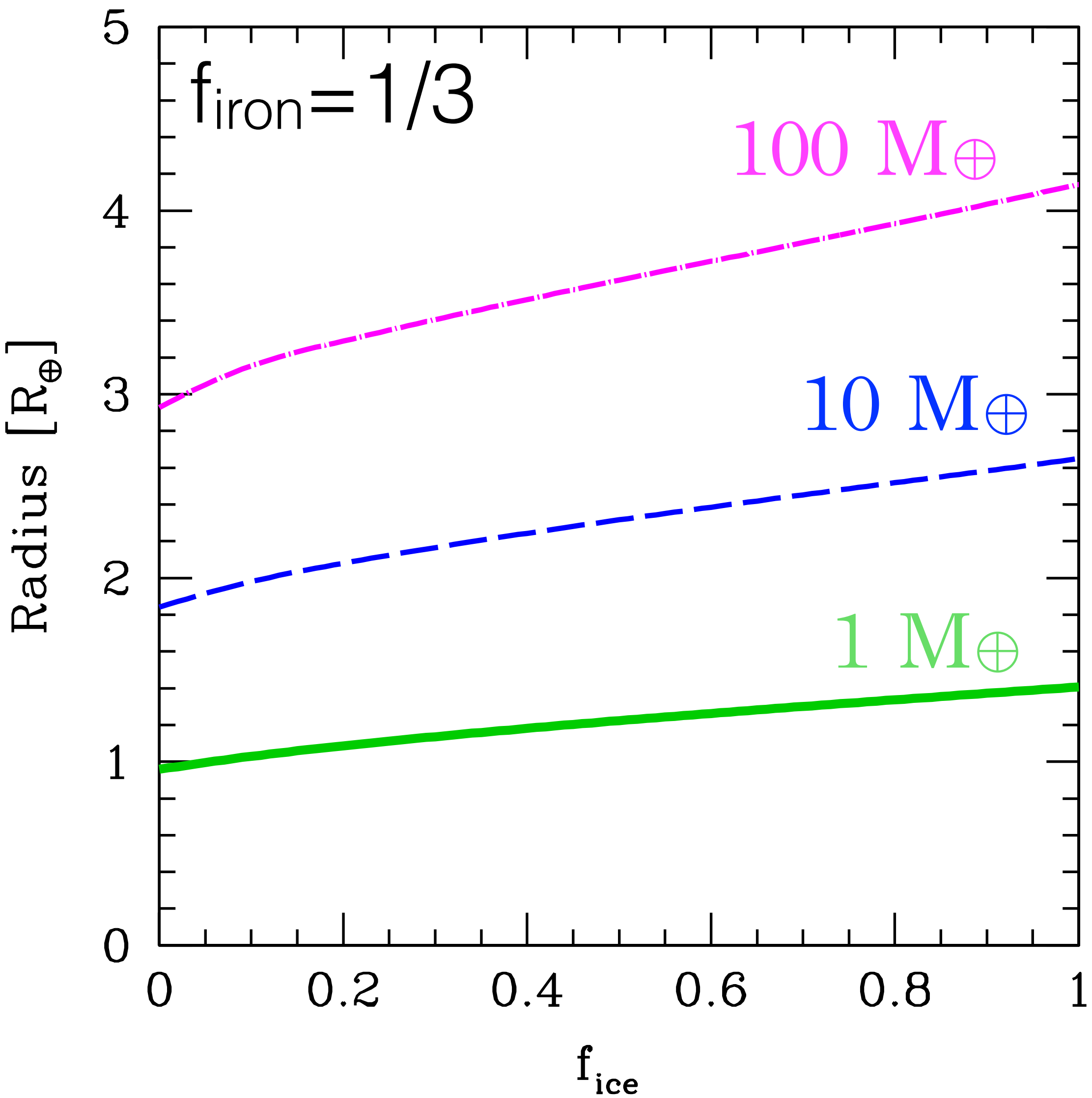


Fe mass fraction

mass %	Corot-7	Kepler-93	Kepler-10	Sun	Sun (L03)	
H	74.83	75.09	74.77	75.06	74.91	
He	23.61	23.69	23.61	23.68	23.77	
H	0.80	0.55	0.90	0.50	0.51	
CH	0.32	0.37	0.36	0.37	0.29	
Fe	0.13	0.09	0.09	0.12	(0.17)	
MgSiO	0.30	0.07	0.16	0.25	(0.27)	
Mg	0	0.14	0.09	0.03		
SiO	0.005	0	0	0		
Z	1.56	1.21	1.61	1.26	1.32	
f	29.4	29.1	25.6	31.0	38.0	32.6%
f	70.6	70.9	74.3	69.0	62.0	



Inferring the ice mass fraction



Planets in bare core triangle

- no H/He
- assume fixed Earth-like Fe:Silicate fraction for *all* planets (f_{iron}=1/3)

=> can invert

$$M, R \Rightarrow \rho_{\rm nom} \Rightarrow f_{\rm ice,nom}$$

preliminary simplistic analysis:

Future work

-use actual stellar composition

-better treatment of errors

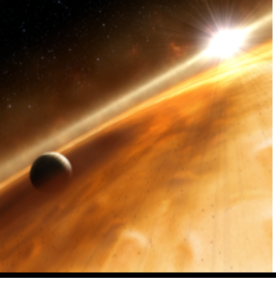
-several interior, EOS & evap. models

Errors in M and R

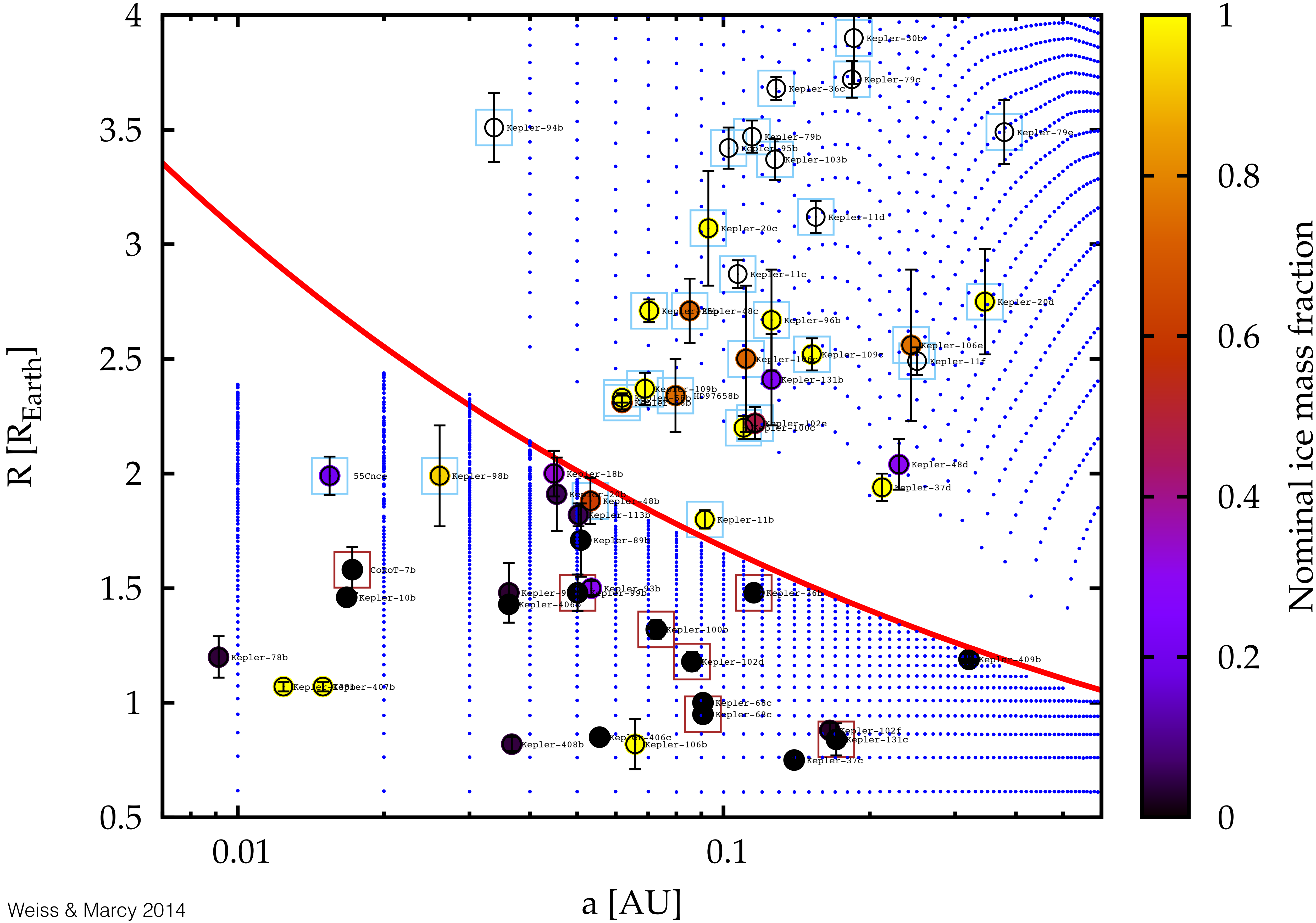
$$M + \sigma_M, R - \sigma_R \Rightarrow \rho_{\rm max} \Rightarrow f_{\rm ice,min}$$

$$M - \sigma_M, R + \sigma_R \Rightarrow \rho_{\rm min} \Rightarrow f_{\rm ice,max}$$

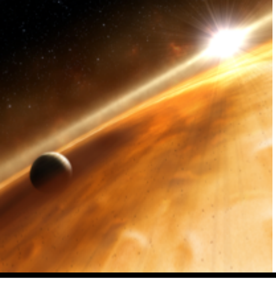
ice presence only constrained if $f_{\rm icemin}$>0



The ice mass fraction, revealed (?)



Obs: Weiss & Marcy 2014



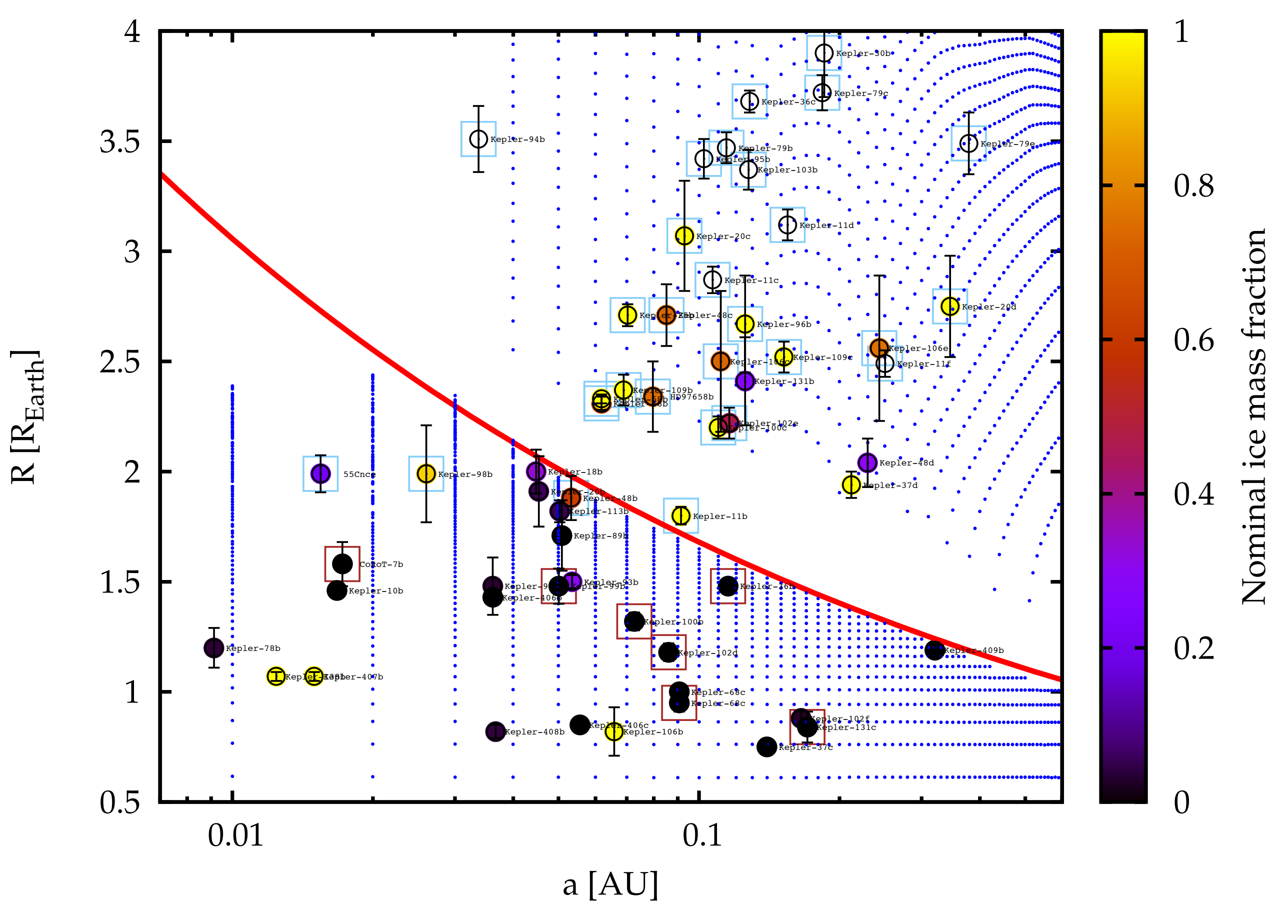
The ice mass fraction, revealed (?)

	M	R	f_{ice}
55 Canc e	8.3±0.4	1.99±0.07	0.03 - 0.20, - 0.34
K-98 b	3.6±1.6	1.99±0.22	0.23- 0.94 - ≥1
K-48 b	3.9±2.1	1.88±0.10	0.11-0.62 -> ≥1

Orbital migration

Atmospheric spectra!

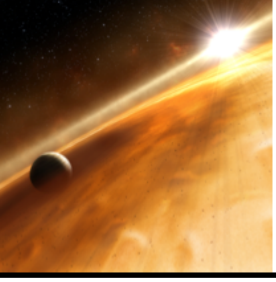
55 Canc e: Demory et al. 2011: 20% ice, but see Demory et al. 2015, Madhusudhan et al. 2012, Alibert submitted



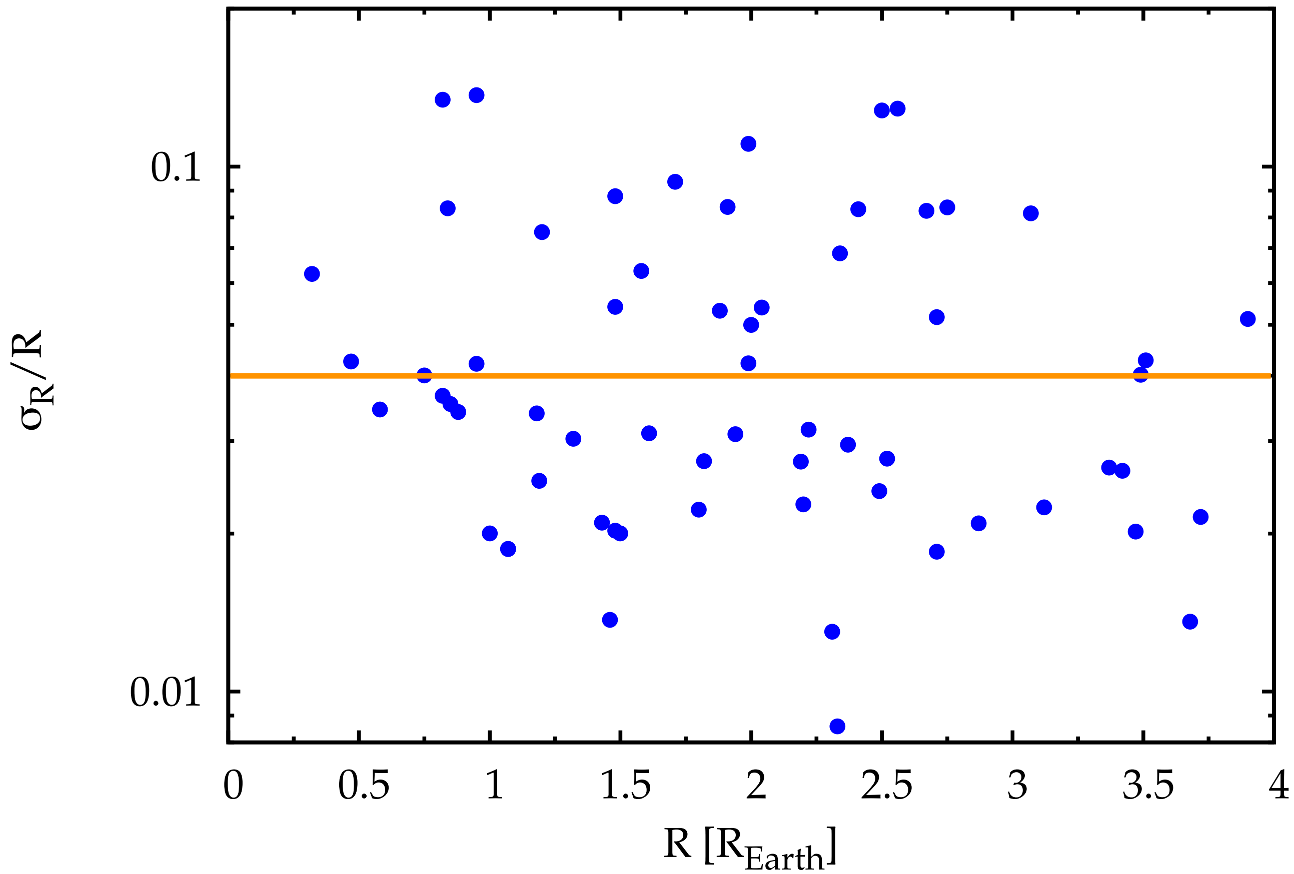
Statistics: 57 planets (solar-like host, M>0)

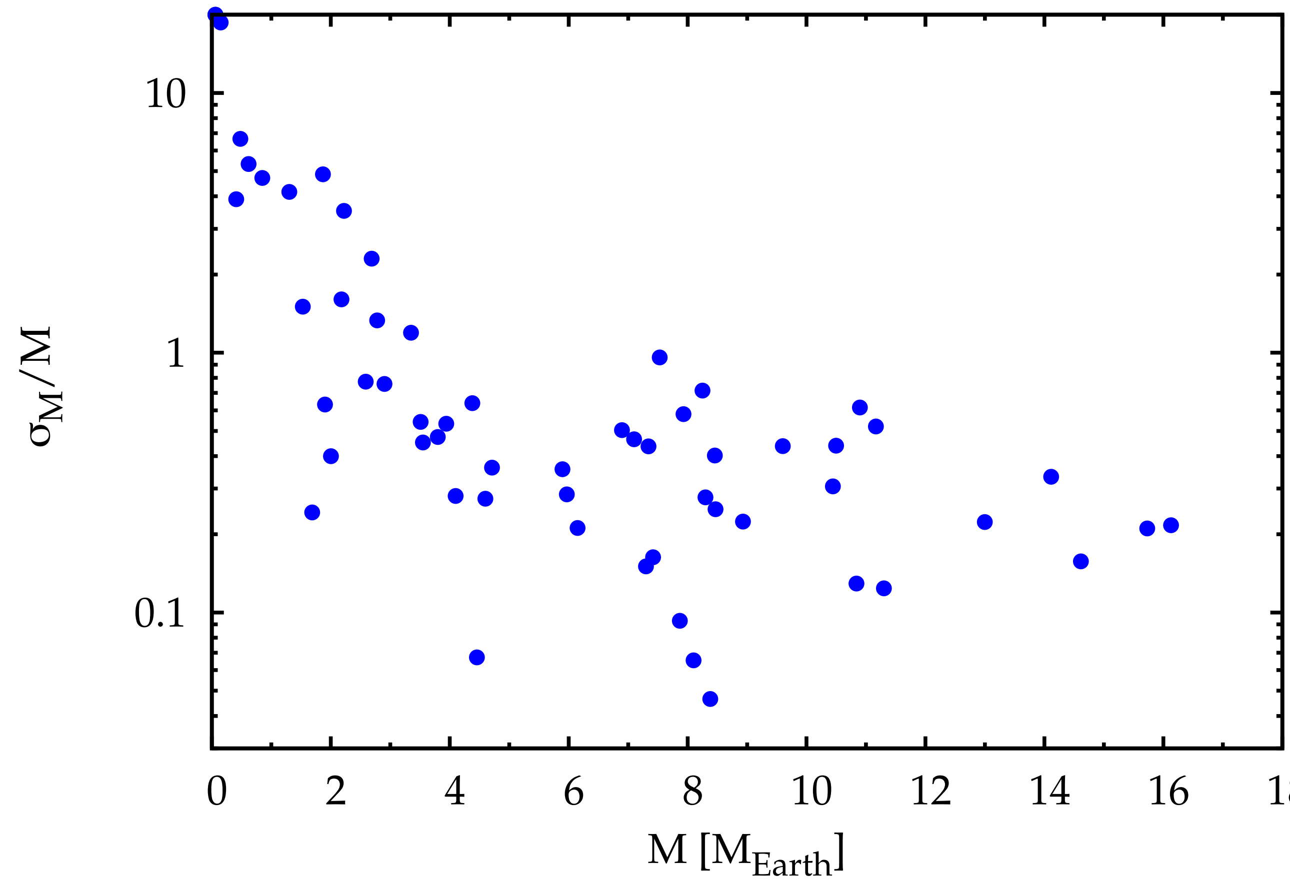
a) 29 outside bare core triangle
- -3 unconstrained
- -0 constrained rocky
- -11 constrained with H/He
- -15 constrained with H/He or ice

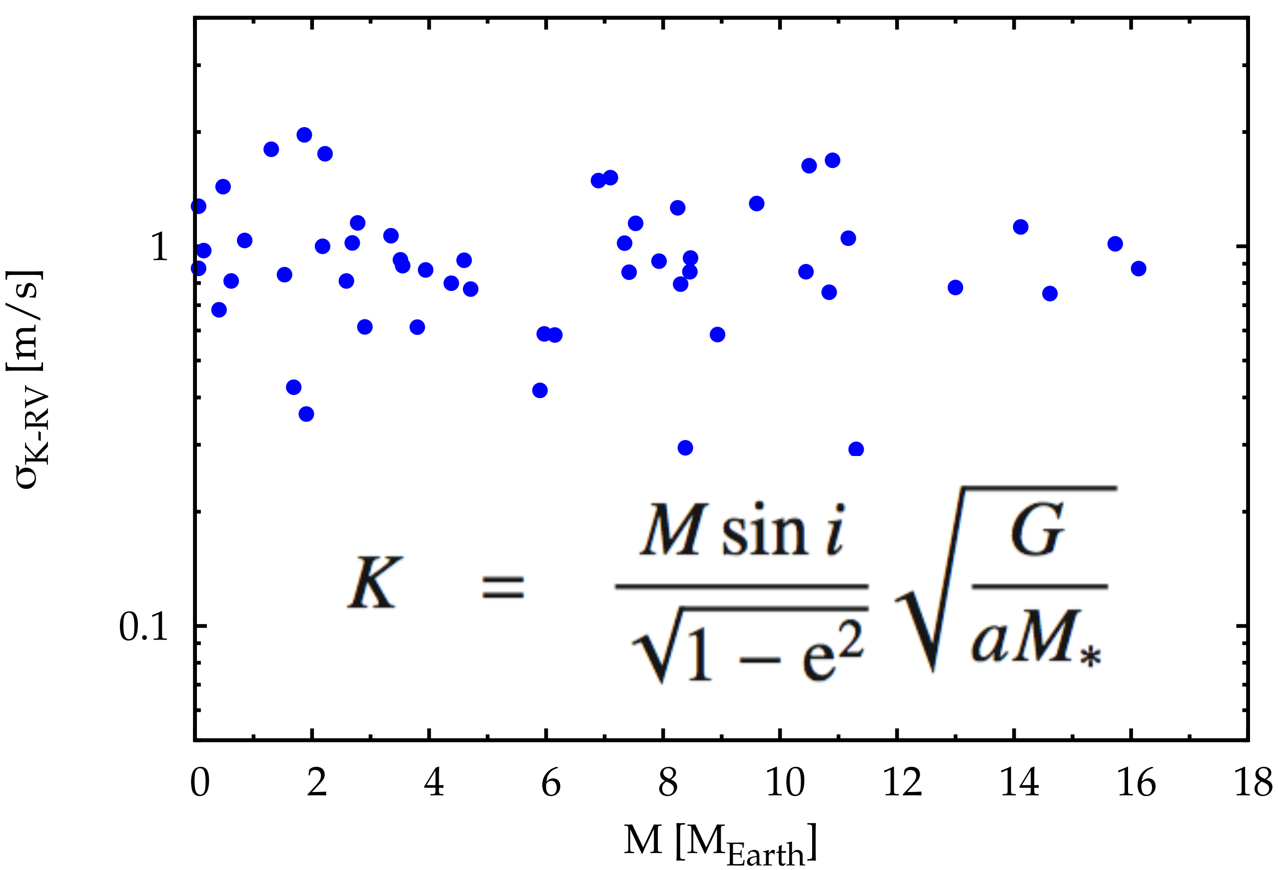
b) 28 in the bare core triangle
- -18 unconstrained
- -7 constrained rocky
- -3 constrained with ice (but…)



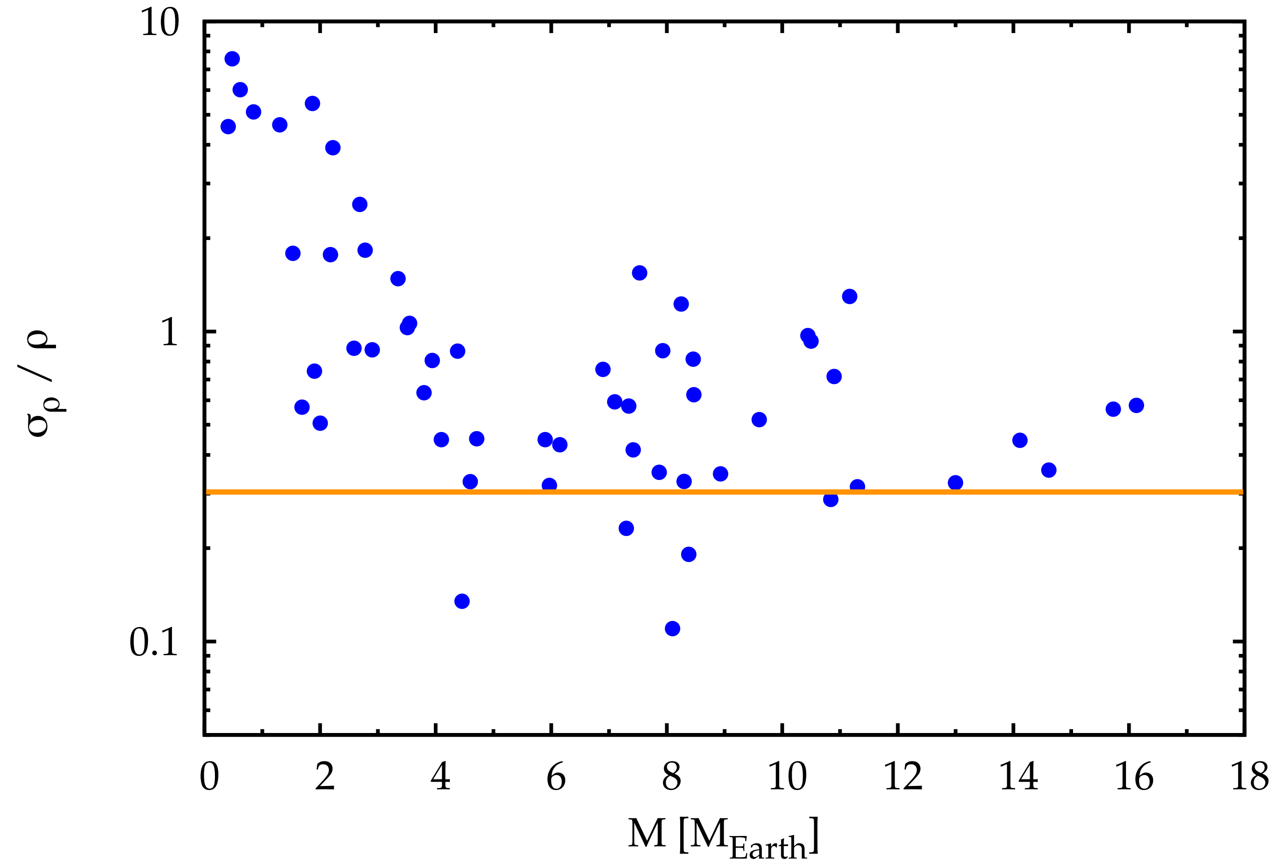
Impact of M and R errors

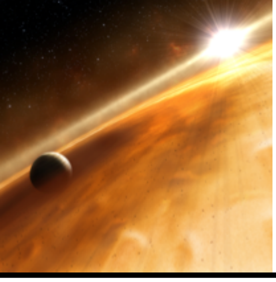






$$K = \frac{M \sin i}{\sqrt{1 - e^2}} \sqrt{\frac{G}{a M_*}}$$





Reducing the errors

Statistics: 57 planets (solar-like host, M>0)

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b) 28 in the bare core triangle
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- -3 constrained with ice (but…)

Effect of reducing error in radial velocity measurement $\sigma_{K\text{-}RV}$ [m/s]

	WM14	0.6 m/s	0.3 m/s	0.1 m/s
unconstrained outside	3	2	1	0
unconstrained inside	18	14	9	7

Conclusions

- Ice mass fraction of close-in low-mass planets: key constraint
- M-R degeneracy reduced by taking into account
  - temporal dimension } atmospheric escape
  - orbital distance } atmospheric escape
  - chemical composition of host star
- Simple analytical models for
  - transition gaseous-solid planet: M_{bare} / R_{bare}
    - All start with primordial H/He. No outgassing.
  - link stellar photospheric composition - planetary iron mass fraction
    - Earth like values expected for Corot-7b, Kepler-10b, Kepler-93b
- Simplistic analysis of bulk composition of WM14 sample
  - 3 planets might have massive ice shells: orbital migration. But…
  - Much more refined analysis necessary
- Useful for analysis of input of M and R errors: low $\sigma_{K\text{-}RV}$ <1 m/s needed