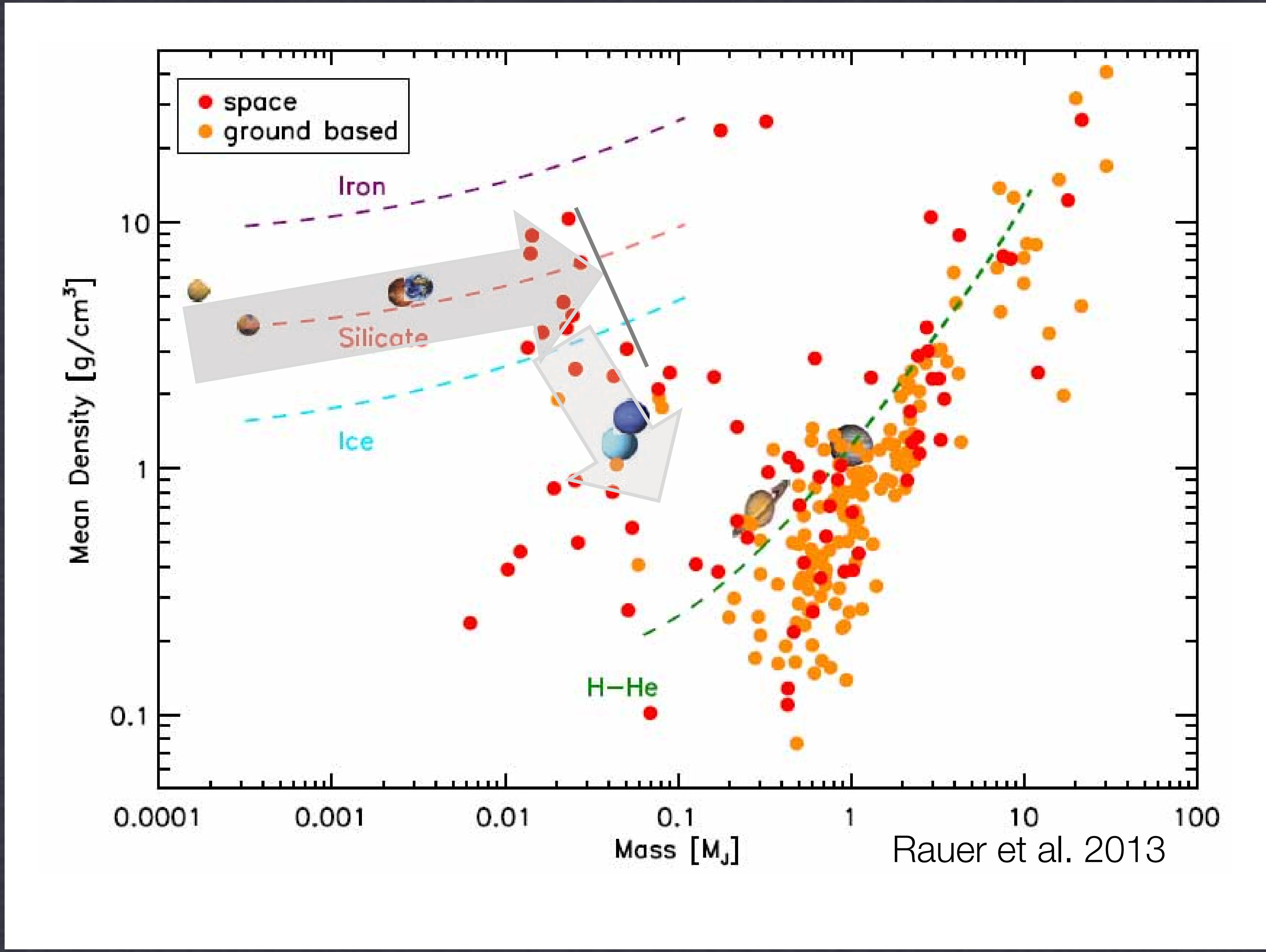
Planet population modelling



PLATO 2.0 Workshop, ESTEC
31.7.2013

Christoph Mordasini

Max Planck Institut for Astronomy, Heidelberg, Germany
S. Jin, K. M. Dittkrist, P. Mollière, G. Marleau, H. Klahr, T. Henning

Y. Alibert & W. Benz, University of Bern, Switzerland

UNIVERSITÄT BERN

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2. Population wide mass-radius relationship
3. Impact of envelope evaporation

1.
Introduction & population synthesis method

Introduction

Planet formation is a complex process

- Huge dynamical range in size/mass: grains to giant planets
- Multiple input physics: gravity, hydrodynamics, radiative transport, thermodynamics, magnetic fields, impact physics, material properties, ...
- Feedbacks and interactions (e.g. gas disk-planet: orbital migration)

Planet formation and evolution difficult to understand purely from first principles.

⇒ Theory needs observational guidance: comparison of observations and theoretical predictions

⇒ Surveys (HARPS, Kepler, PLATO) yield large numbers of exoplanets: no more “just” single objects, but populations characterized by distributions

⇒ Statistical comparison: planetary population synthesis

or exoplanet candidates like don likes to precise

Population Synthesis Principle

Global formation & evolution model

Link disk properties ⇒ planet properties

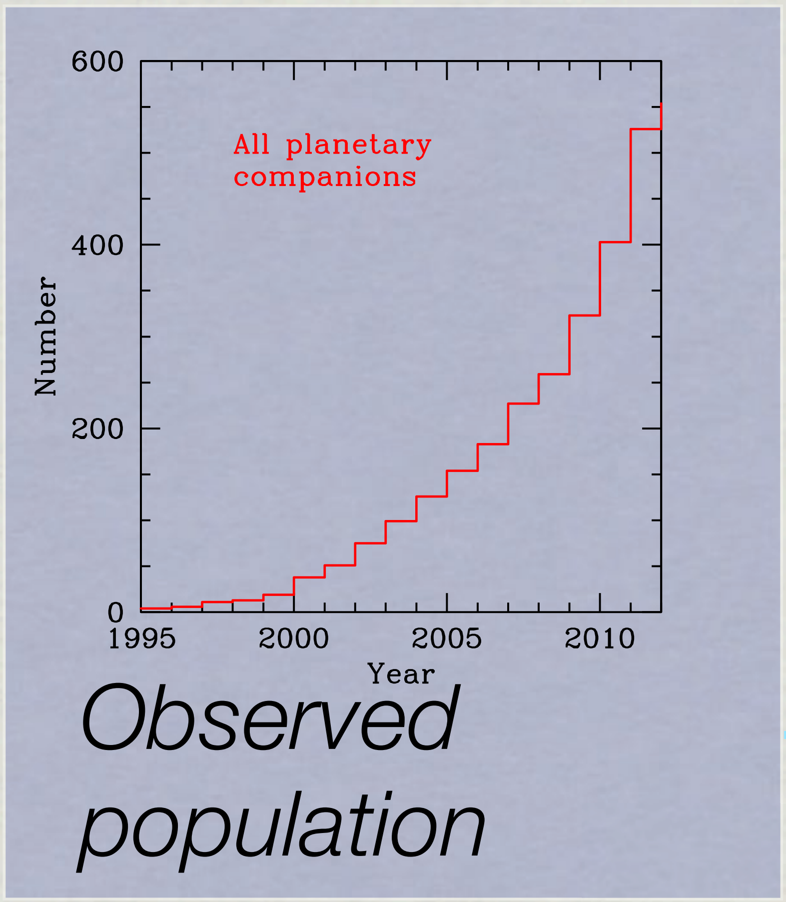
Initial Conditions: Probability distributions & parameters

Disk gas mass
Disk dust mass
Disk lifetime

From observations

Draw and compute synthetic planet population

Apply observational detection bias



Comparison:

Observable sub-population
- Distribution of semi-major axis
- Distribution of masses
- Distribution of luminosities
- Distribution of radii

No match: improve, change parameters

Match

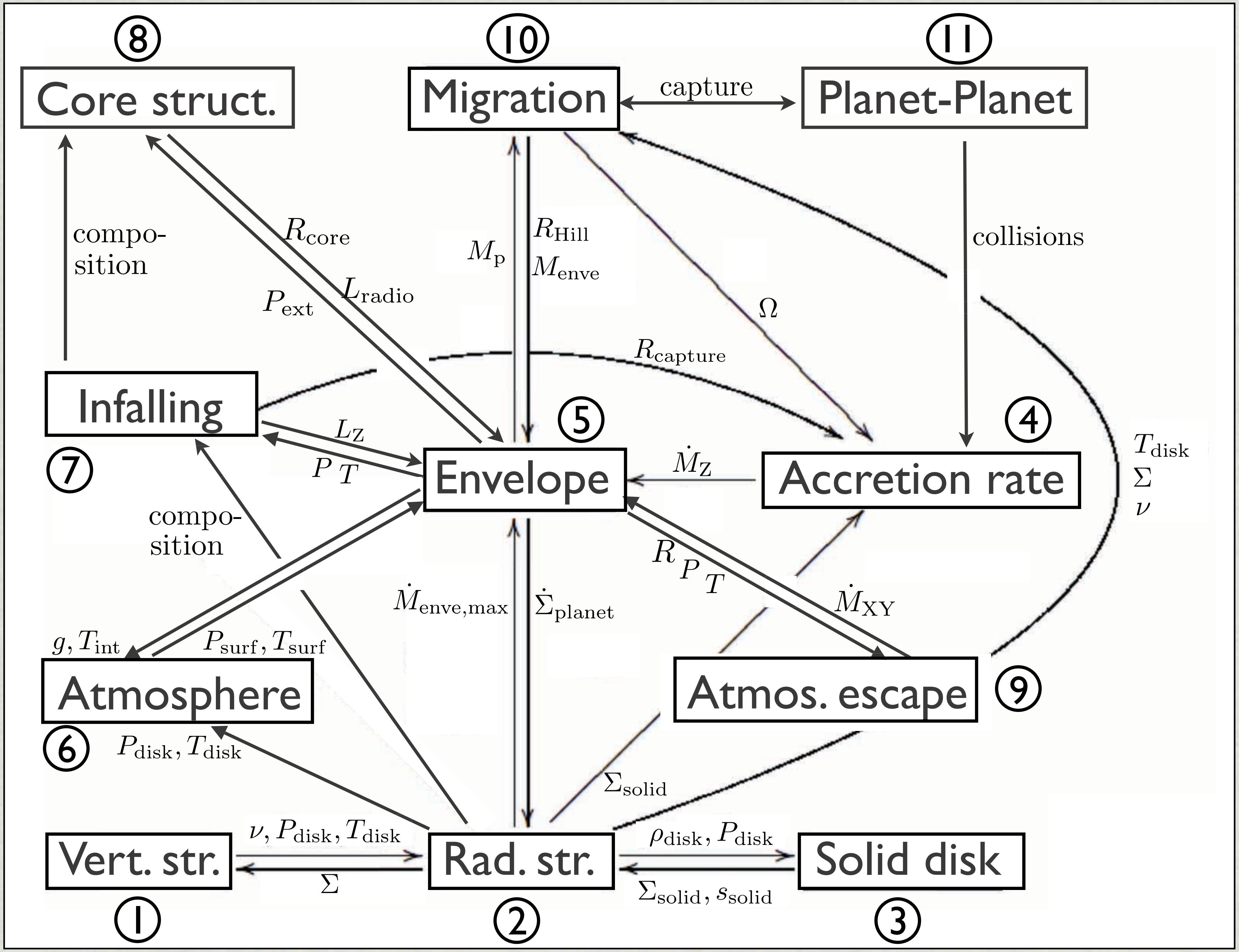
Model solution found

Predictions

(going back to the full synthetic population)

Ida & Lin 2004-2013, Thommes et al. 2008, Mordasini et al. 2009-2012, Miguel et al. 2011, Hellary & Nelson 2012

Global formation & evolution model



Alibert, Mordasini, Benz 2004; Alibert et al. 2005, Mordasini et al. 2012, Fortier et al. 2013, Alibert et al. 2013

based on core accretion paradigm

protoplanetary disk evolution

+

Planet model (gas & solid accretion, interior structure)

+

orbital migration

+

N-body

Simple standard models but coupled together.

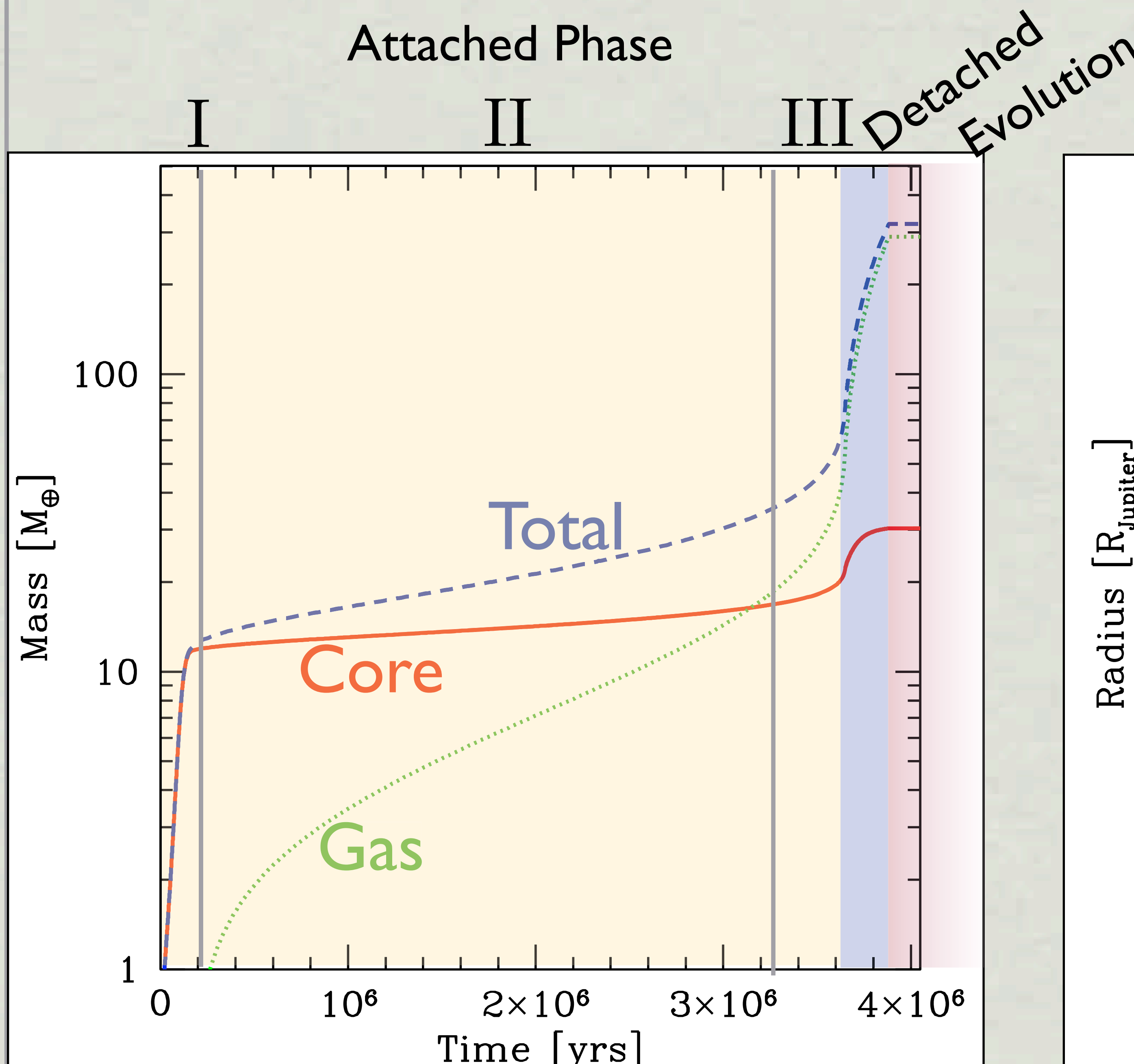
Example: Jupiter in situ formation

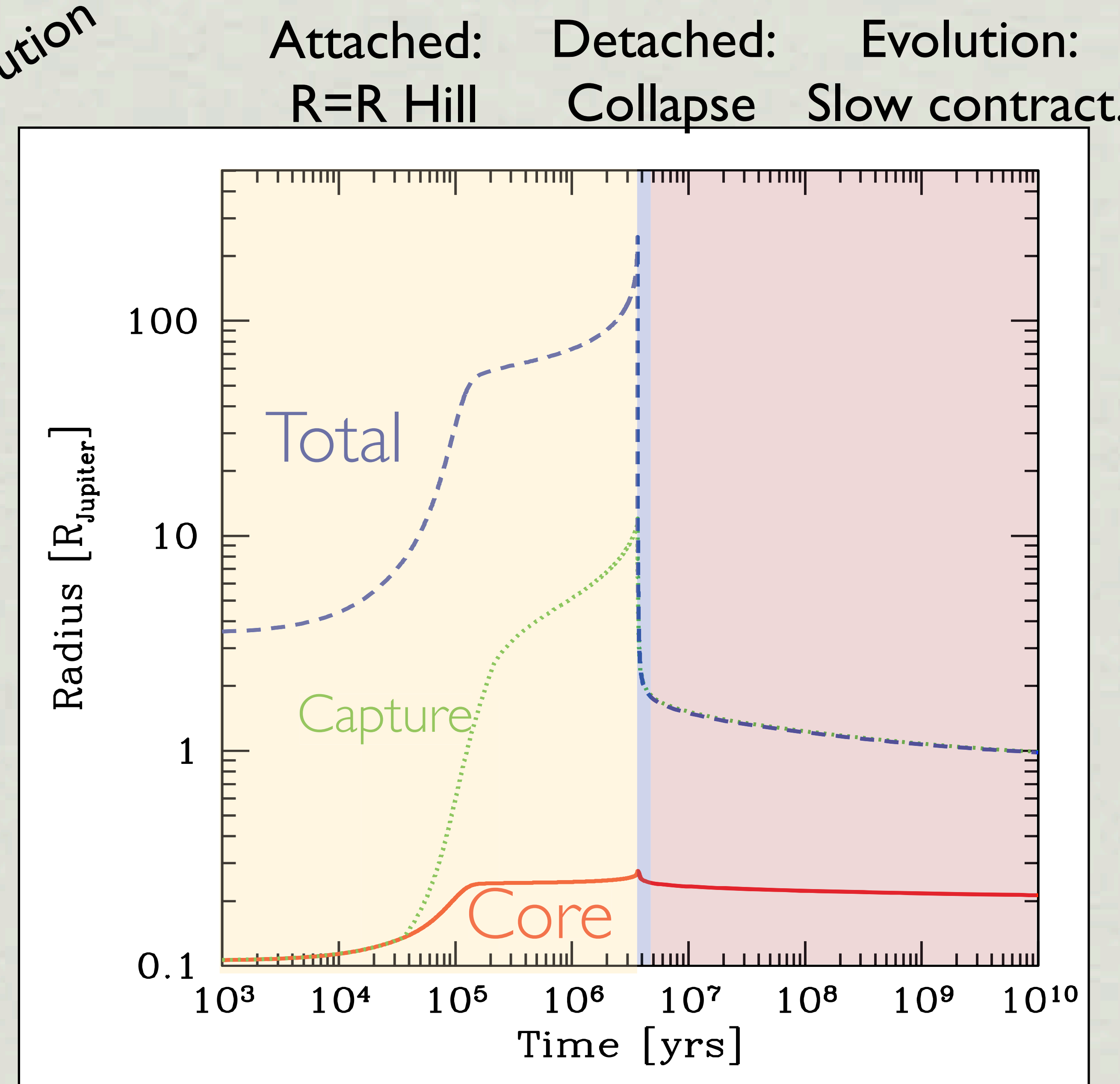
Model assumptions:

Pollack et al 1996

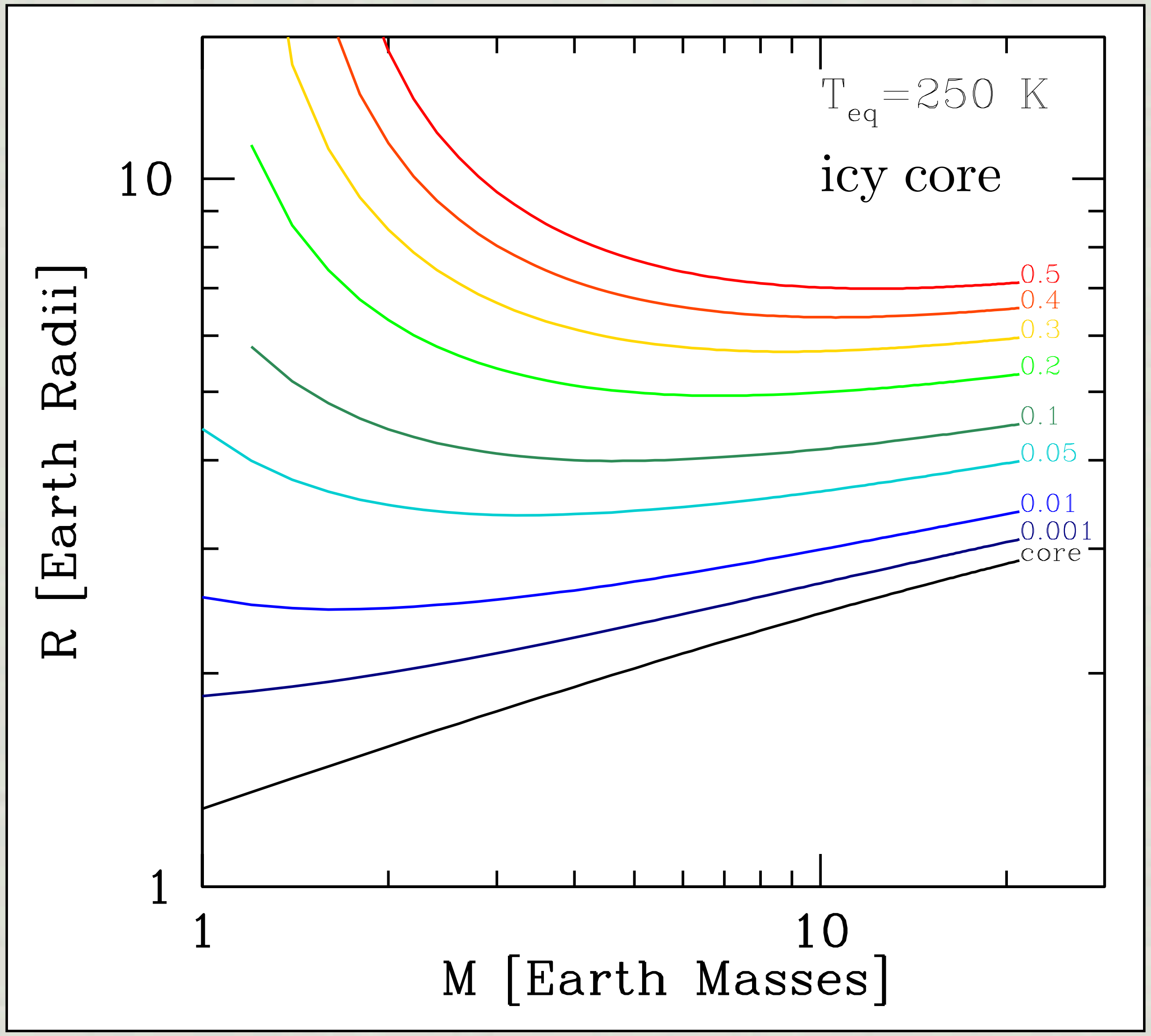
- Constant ambient T and P (no disk evolution)
- In situ formation (no migration)
- One planet only (no N-body)

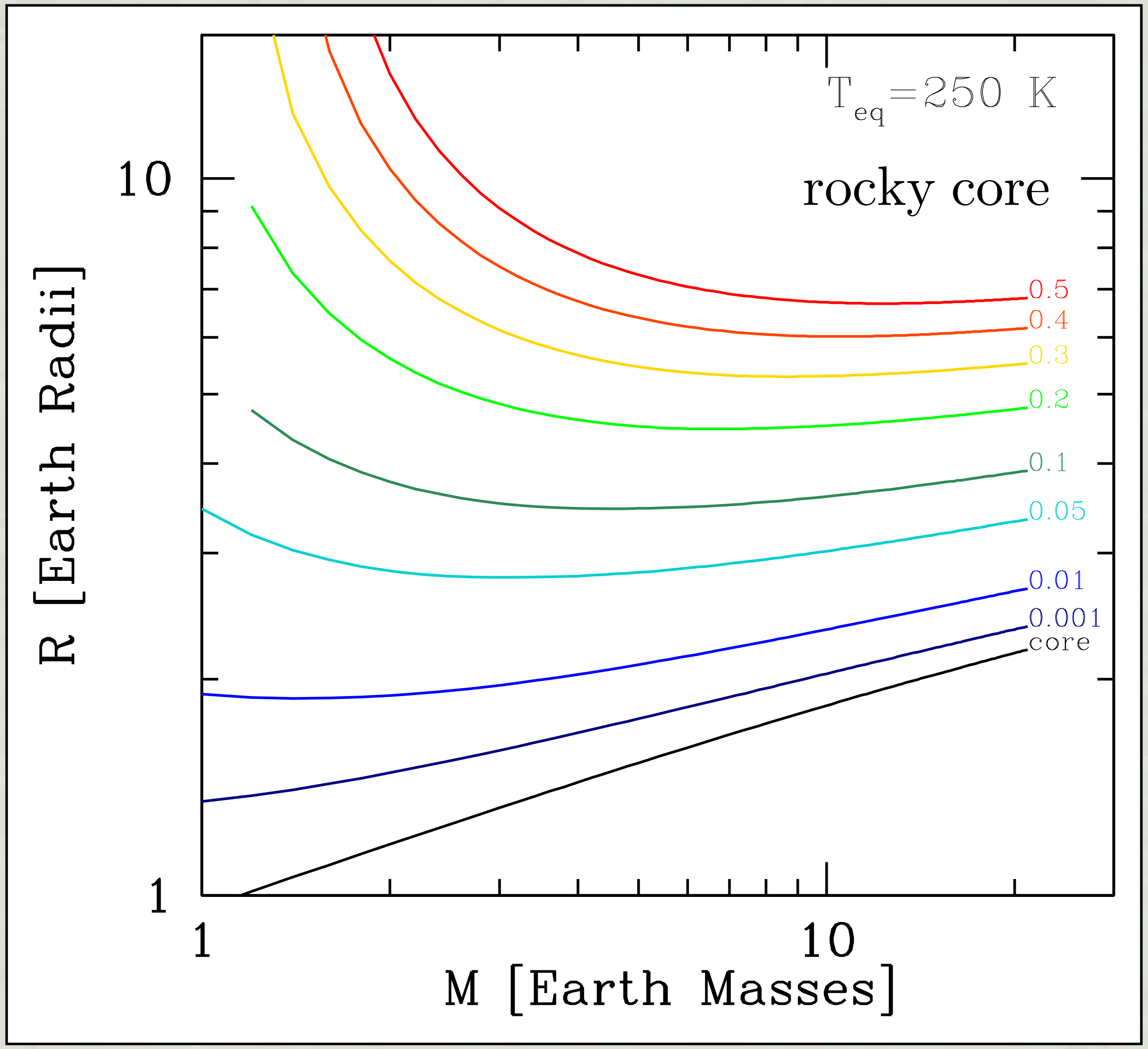
•Before gas runaway accretion: $R \approx R_{Hill}$ (attached)
•Gas runaway accret., detachment and collapse
•Slow contraction during evolution at constant mass over Gyrs





MRR: low-mass planets with H/He

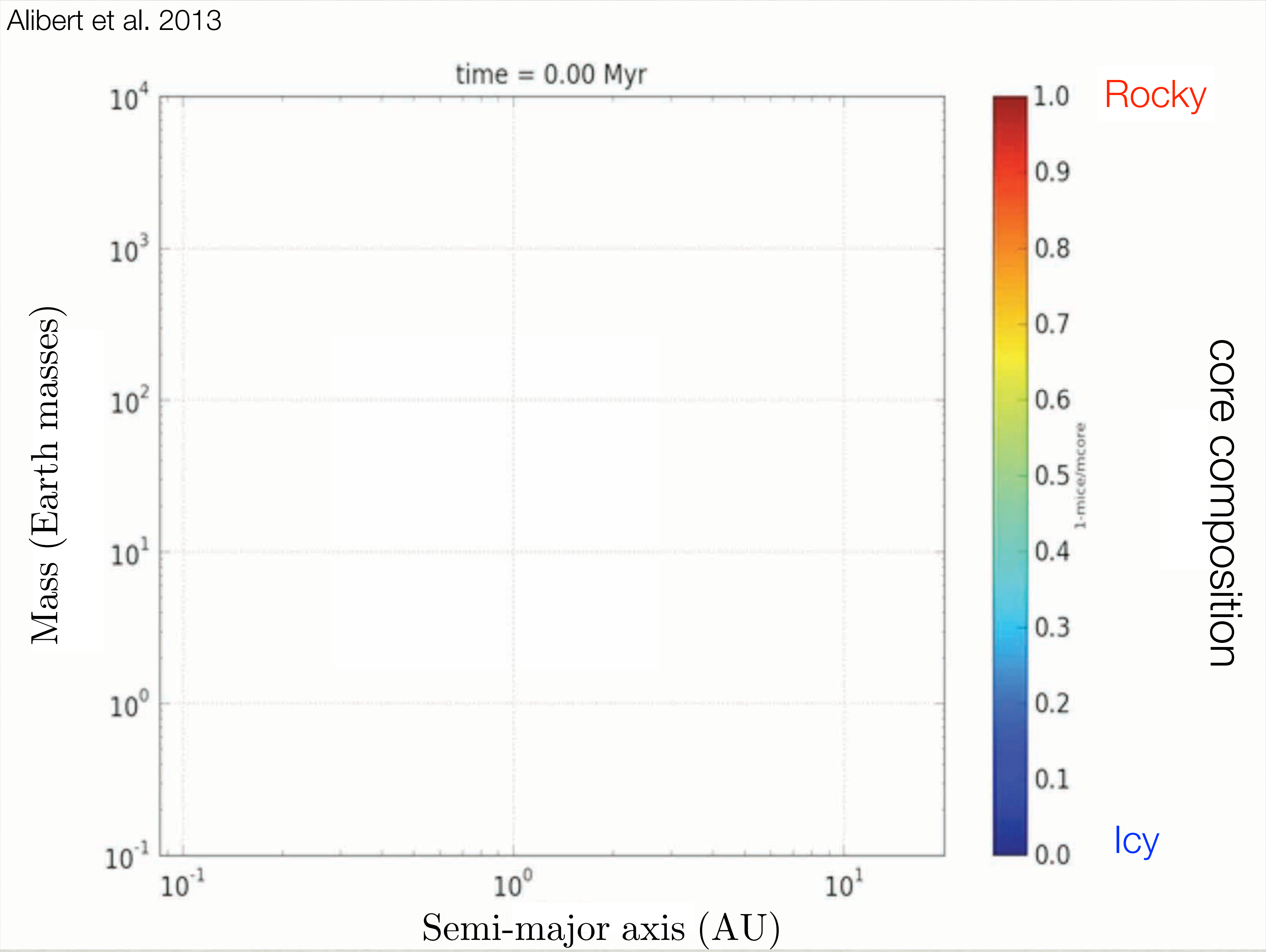




- Small amount of H/He=> strong R increase
- M-R “inversion” for high gas fractions
- Degeneracy of possible compositions
- Temperature (distance) dependence

Mordasini et al. 2012, cf Rogers et al. 2011

Synthesis: Formation tracks

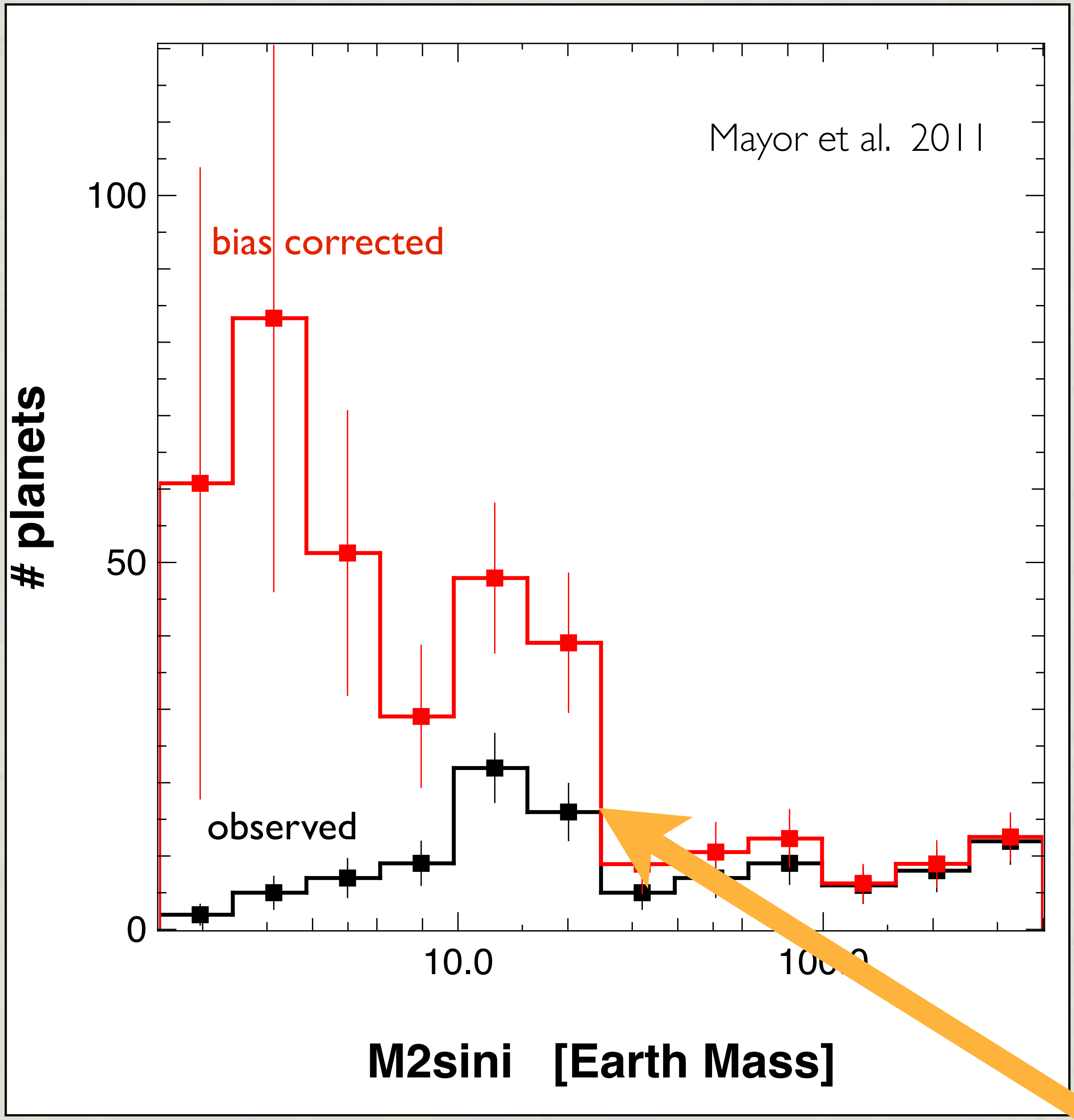


1 M_{sun} star - 100 planetary systems - 10 planets/system - nonisothermal type I

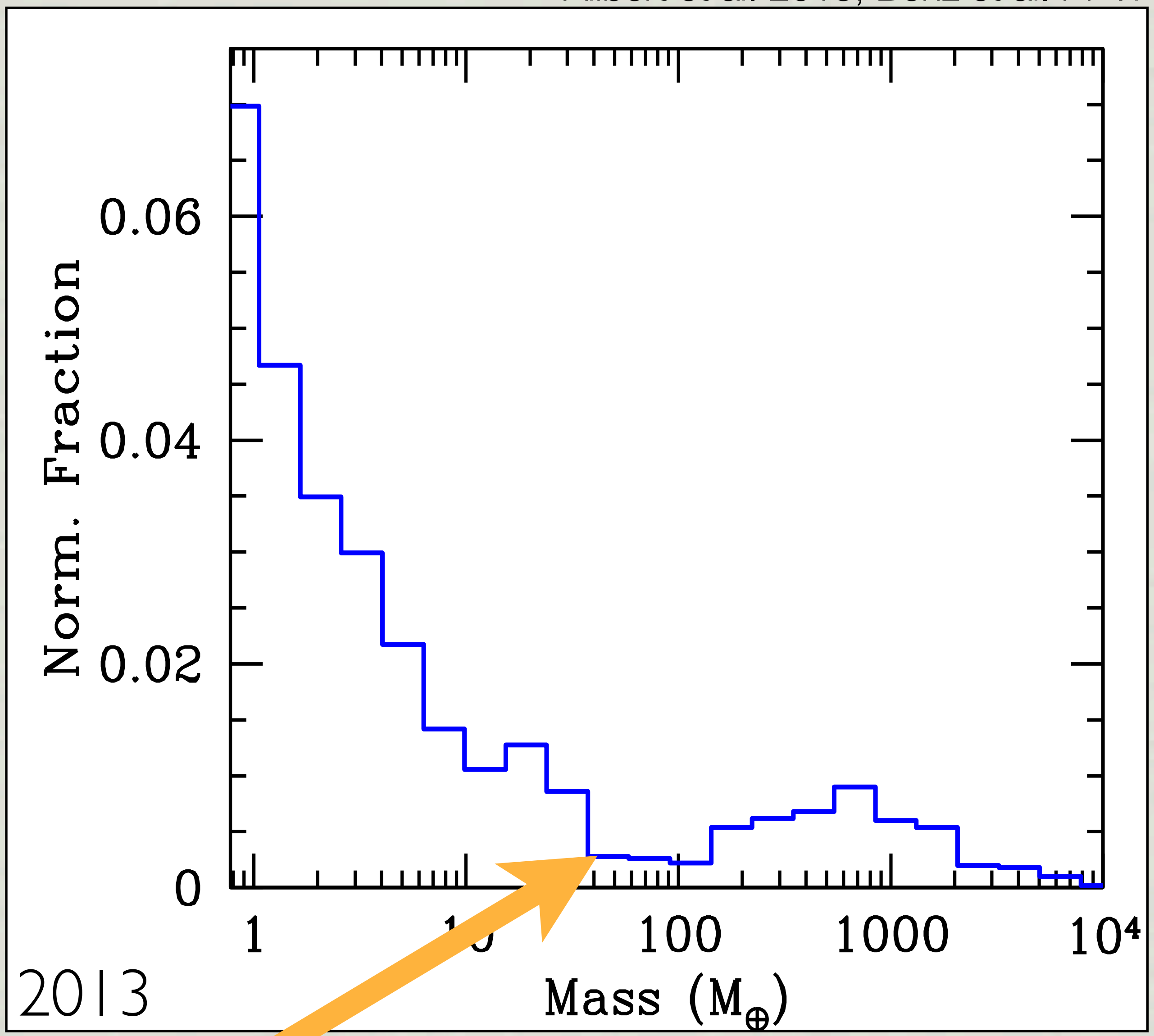
Planetary initial mass function

Observed mass function (HARPS)

Mordasini et al. 2009



Alibert et al. 2013, Benz et al. PPVI



10 embryos/disk (N-body)
starting mass: 0.01 M_{Earth}

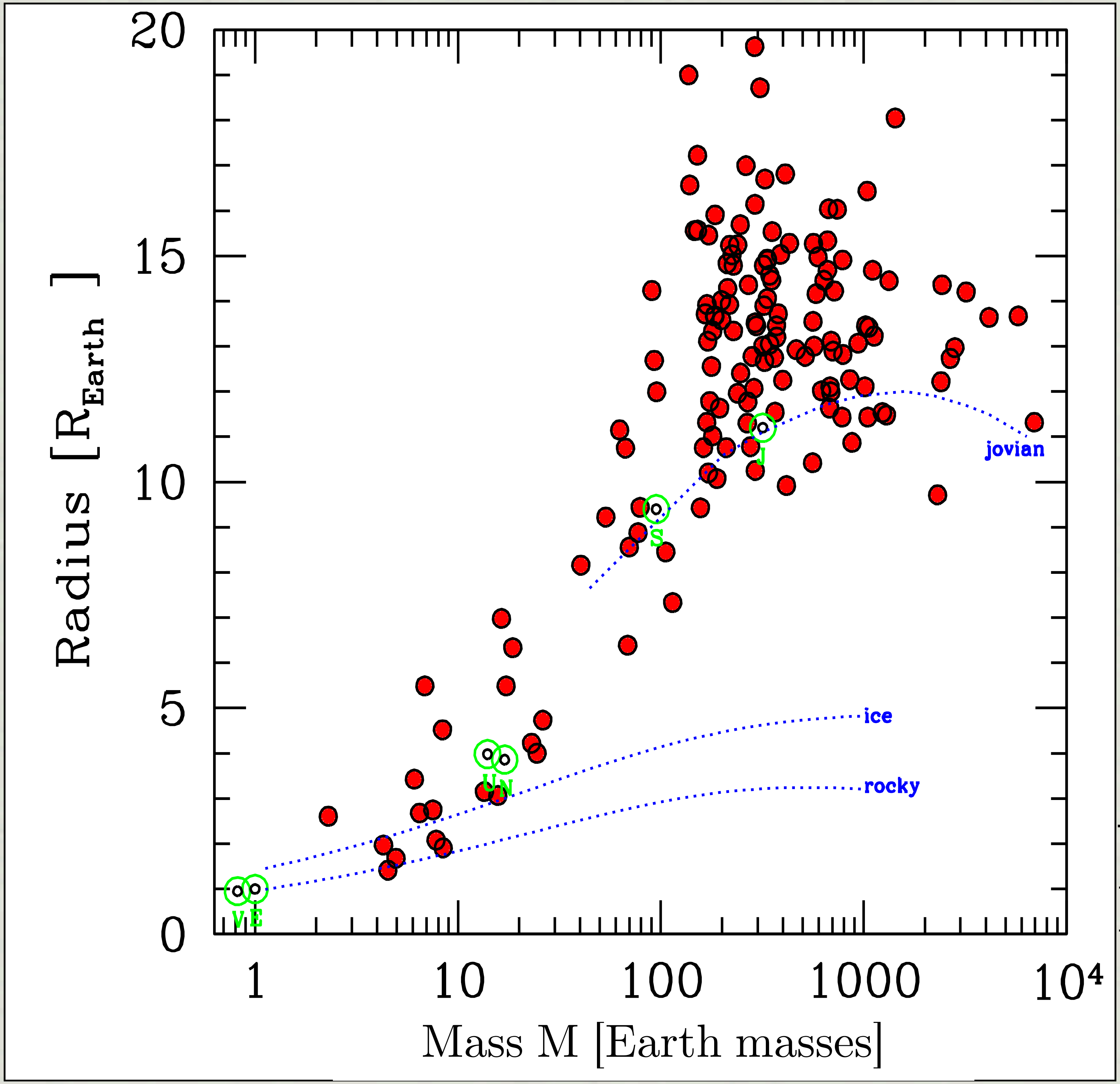
Sudden increase

Typical for core accretion. Constraint on M_{crit} & gas accretion rate (IL04).

Many low-mass planet - much remains to be discovered.

2.
Population wide mass-radius relationship

Towards a first characterisation



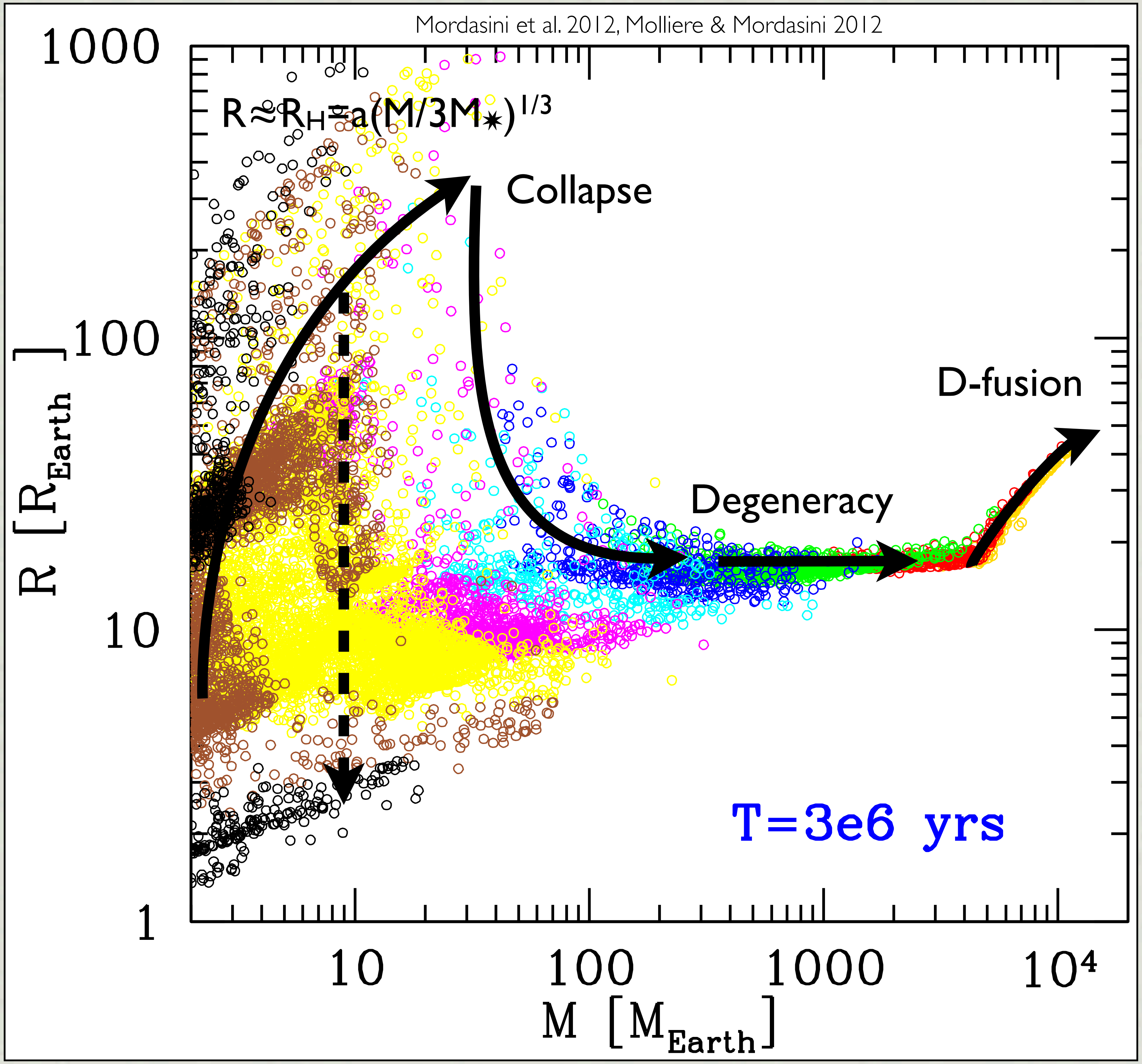
- M-R: First geophys. characterisation: rocky, icy, gaseous

- General trends
- Large diversity
- Inflated giant planets
- Empty regions

- Understandable with theoretical models?
- Constraints for formation theory beyond the a-M:

-migration (icy planets close-in?)
-efficiency of H/He accretion & loss (opacity? atmos. compositions?)

Formation of the M-R relationship



Fraction Z of solids (rest H/He)

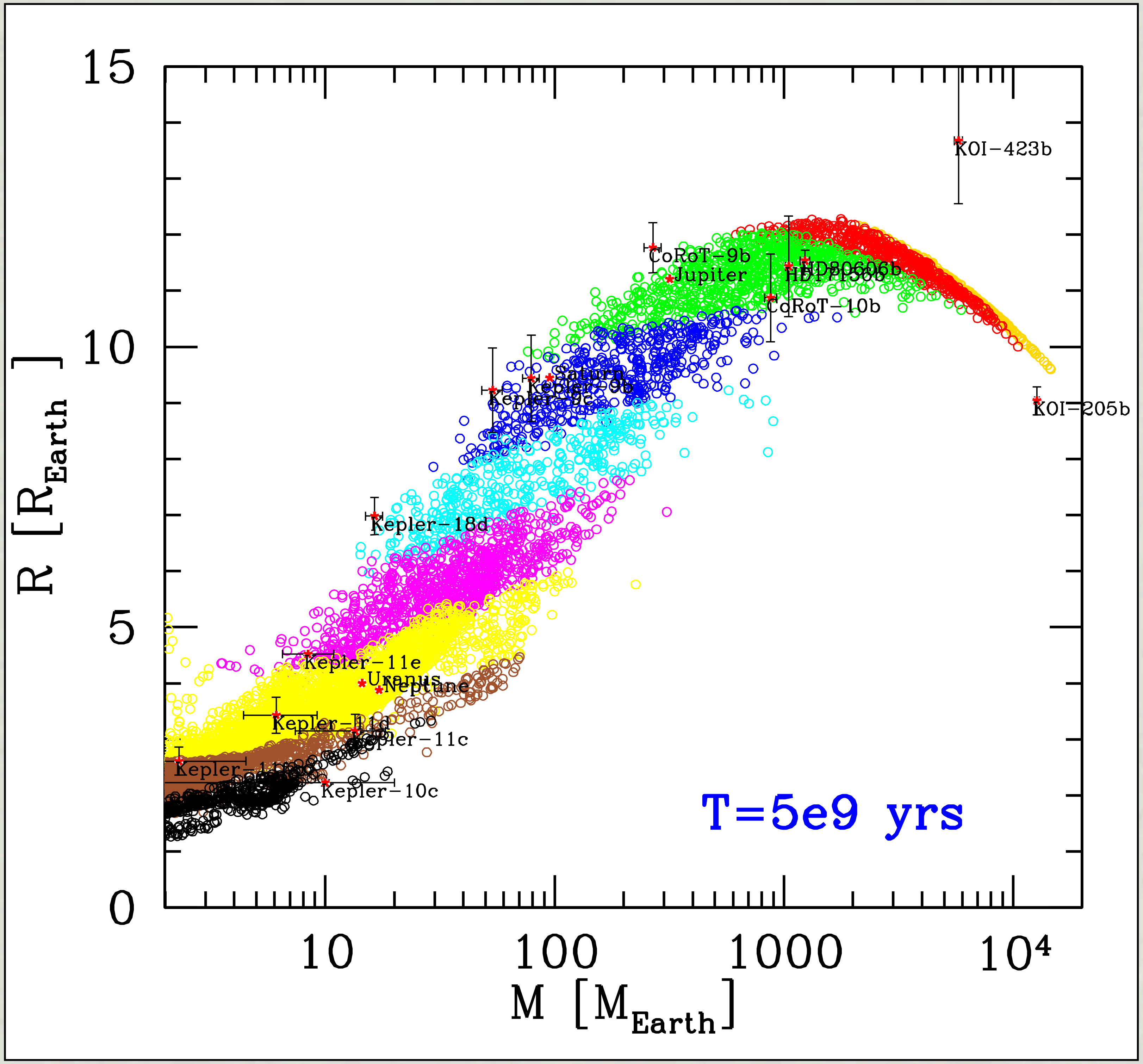
Orange: $Z \leq 1\%$
Red: $1 < Z \leq 5\%$
Green: $5 < Z \leq 20\%$
Blue: $20 < Z \leq 40\%$
Cyan: $40 < Z \leq 60\%$
Magenta: $60 < Z \leq 80\%$
Yellow: $80 < Z \leq 95\%$
Brown: $95 < Z \leq 99\%$
Black: $Z > 99\%$

Rapid collapse at ~0.2 MJ when Z≈ 0.5 (runaway gas accretion)

After disk dispersal (T>10 Myrs), slow contraction.

M_{star}=1 M_{sun}. a>0.1AU. Non-isothermal type I. cold accretion. 1 embryo/disk, no special inflation mechanisms, no evap.

M-R: comparison with observation



All synt. planets and all planets with well known M-R outside 0.1 AU.

S-shape with forbidden zones
- -low M ⇨ high Z ⇨ small R
- -high M ⇨ low Z ⇨ large R

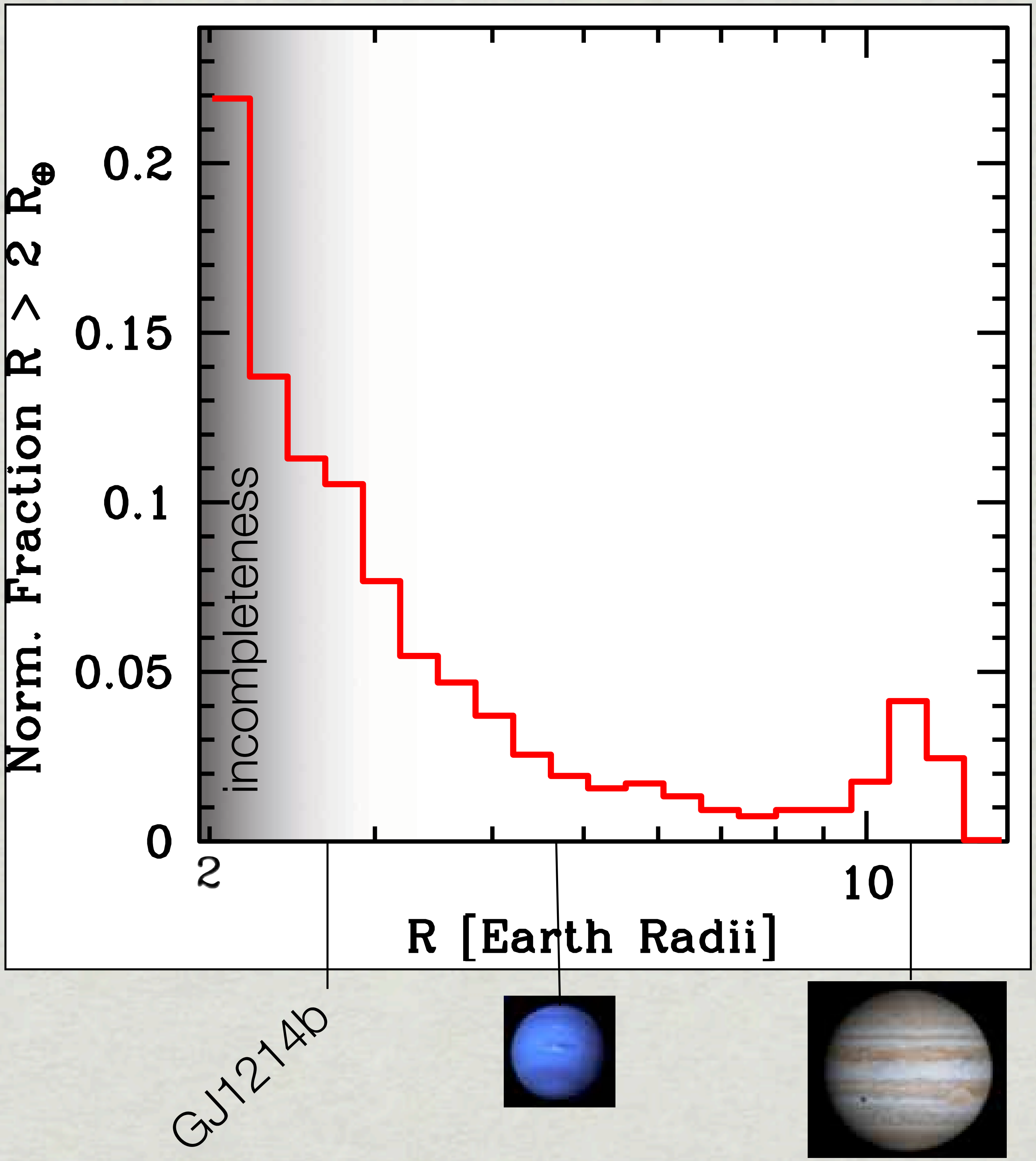
Imprint from core accretion & EOS

Comparison with observations fine except for KOI-423b. To be tested with future observation. Only primordial H/He.

Orange: $Z \leq 1\%$	Yellow: $80 < Z \leq 95\%$
Red: $1 < Z \leq 5\%$	Brown: $95 < Z \leq 99\%$
Green: $5 < Z \leq 20\%$	Black: $Z > 99\%$
Blue: $20 < Z \leq 40\%$	
Cyan: $40 < Z \leq 60\%$	
Magenta: $60 < Z \leq 80\%$	

M_{star}=1 M_{sun}. a>0.1AU. Non-isothermal Type I. Cold accretion. 1 embryo/disk, no special inflation mechanisms, no. evap.

Planetary radius distribution

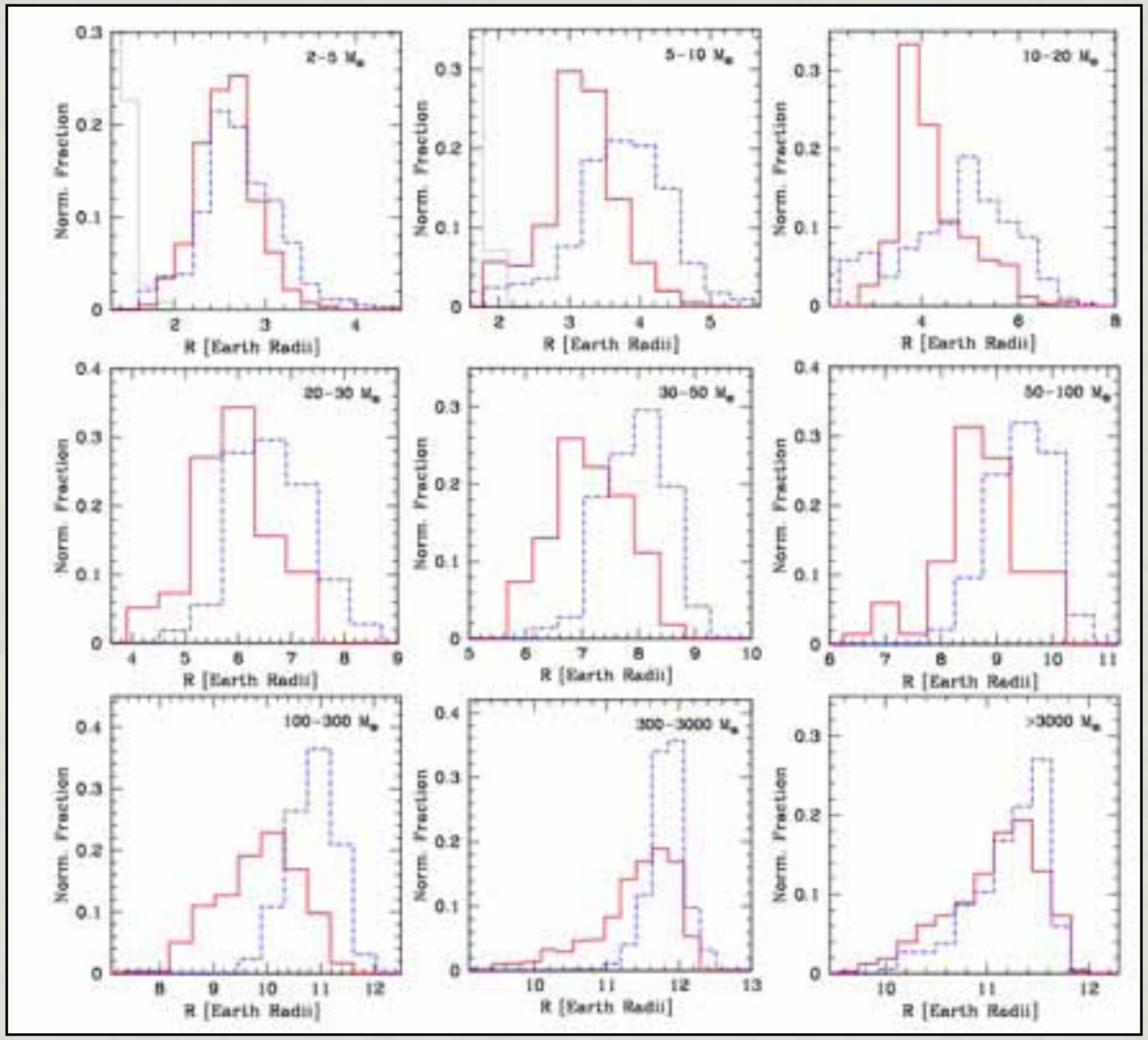


- Radius distribution is *bimodal* (also predicted by Ida & Lin, and Wuchterl)
- Peak at lowest radii. High detection rate for very precise transit missions.
- Only primordial H_2/He atmos: divergence at low radii expected.
- Peak at ~ 1 R_J ⇨ Giant planets have all approx. *the same radius independent of mass* (degeneracy!)
- Bimodality: prediction for PLATO (larger orbital periods).

M_{star}=1 M_{sun}. a>0.1AU. Non-isothermal Type I. Cold accretion. 1 embryo/disk, no special inflation mechanisms, no evap.

M-R conversion

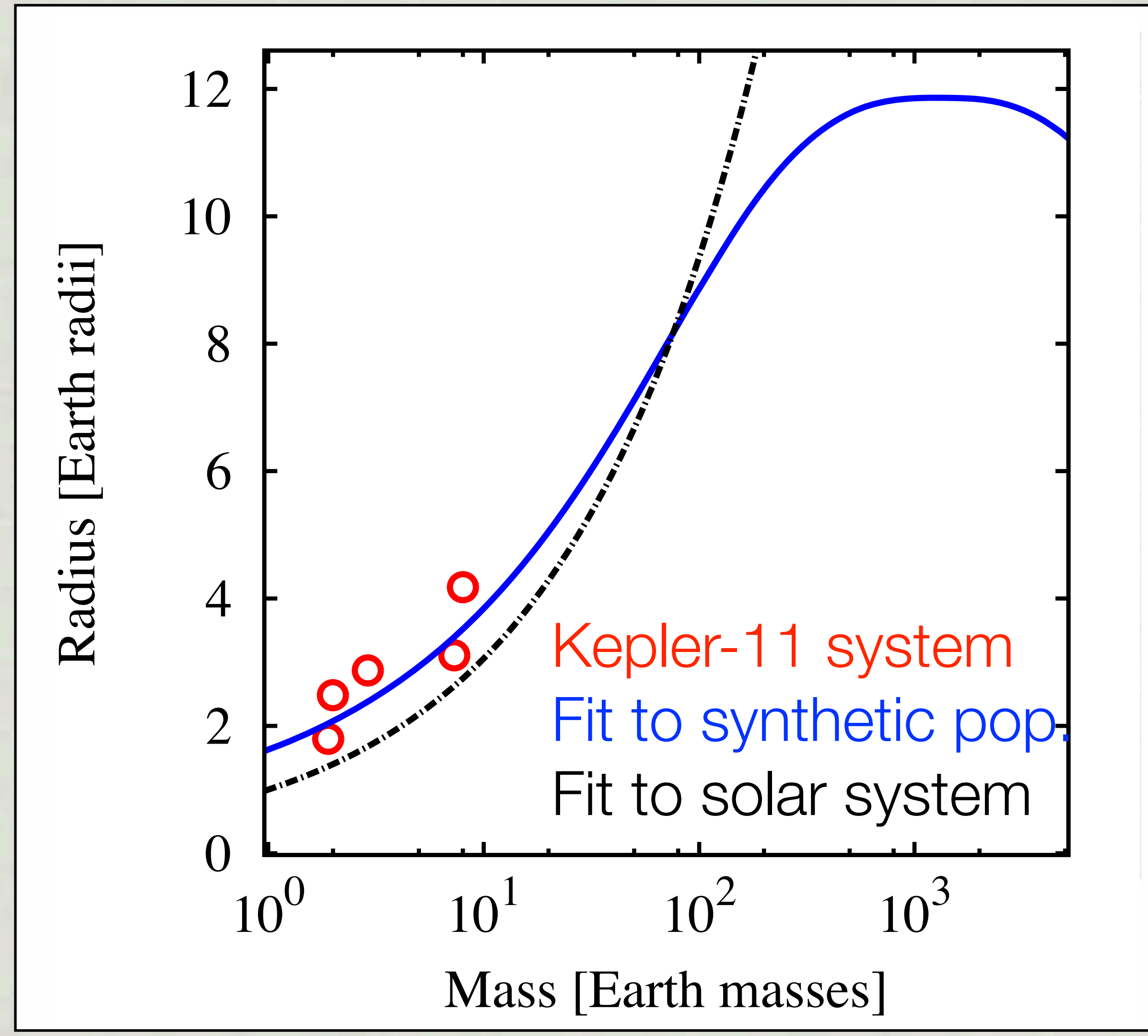
Statistics of the M-R relation



Conversion R into M
Comparison with observations
Planets with primordial H/He

Tables available (Mordasini et al. 2012b).

Mean M(R)



$$\bar{R}(M) = \frac{b}{1 + \left|\frac{\log(M/M_0)}{w}\right|^p}$$

Four parameter fit for the planetary MMR (Traub 2011). Determine parameters for synthetic population.

3.
Impact of atmospheric escape

Envelope evaporation

Couple evolutionary model with mass loss due to atmospheric escape

(e.g.,Lammer et al. 2003, Baraffe et al. 2004, Erkaev et al. 2007, Murray-Clay et al. 2009, Lopez et al. 2013, Owen & Wu 2013)

Flux

$$F_{\rm UV}(t,a) = F_{\rm UV,0}\left(\frac{t}{1\ \rm Gyr}\right)^{-1}\left(\frac{a}{1\ \rm AU}\right)^{-2}$$

UV flux from Ribas et al. 2005.

$F_{UV,0}$ from Lecavelier des Etangs 2007

EUV Loss Rate

$$\dot{M}_{\rm e-lim} = \frac{\epsilon\pi F_{\rm UV} R_p^3}{G M_p}$$

$F_{UV} < \sim 10^4$ erg/(cm^2 s) Energy limited

$$\dot{M}_{\rm rr-lim} \sim 4\pi\rho_{\rm s} c_{\rm s} r_{\rm s}^2 \propto F_{\rm UV}^{1/2}$$

$F_{UV} > \sim 10^4$ erg/(cm^2 s) Radiation-recombination limited (Murray-Clay et al. 2009)

X-ray Loss Rate

$$\dot{M}_X = \frac{4\epsilon_X L_X R_p^3}{3 G M_p a^2 K(\xi)}$$

$F_{UV} < F_{UV,crit}$

Owen & Jackson 2012
Jackson et al. 2012

Roche lobe effect

$$K(\xi) = 1 - \frac{3}{2\xi} + \frac{1}{2\xi^3}$$

$$\xi = R_{roche}/R_P$$

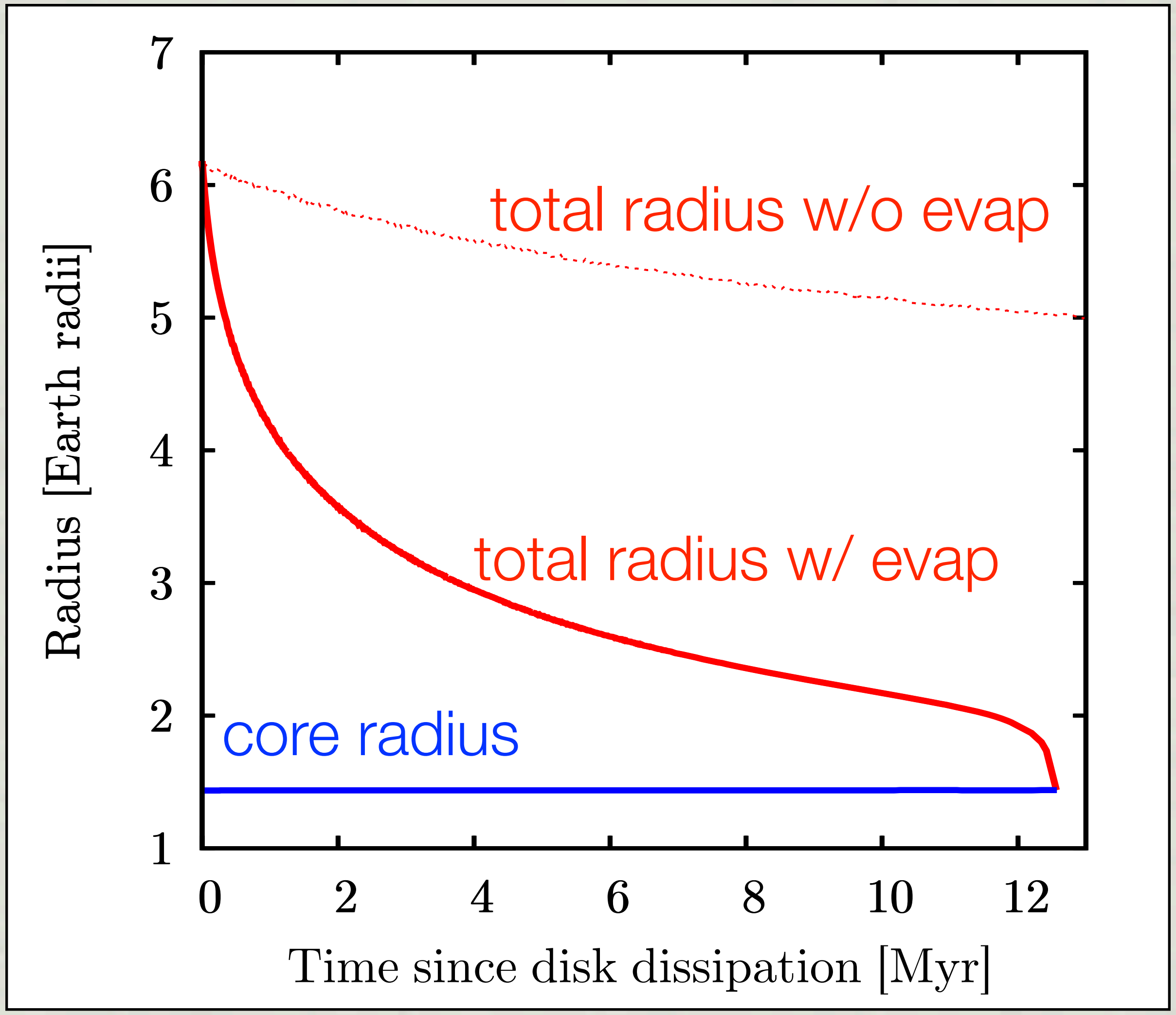
Erkaev et al. 2007

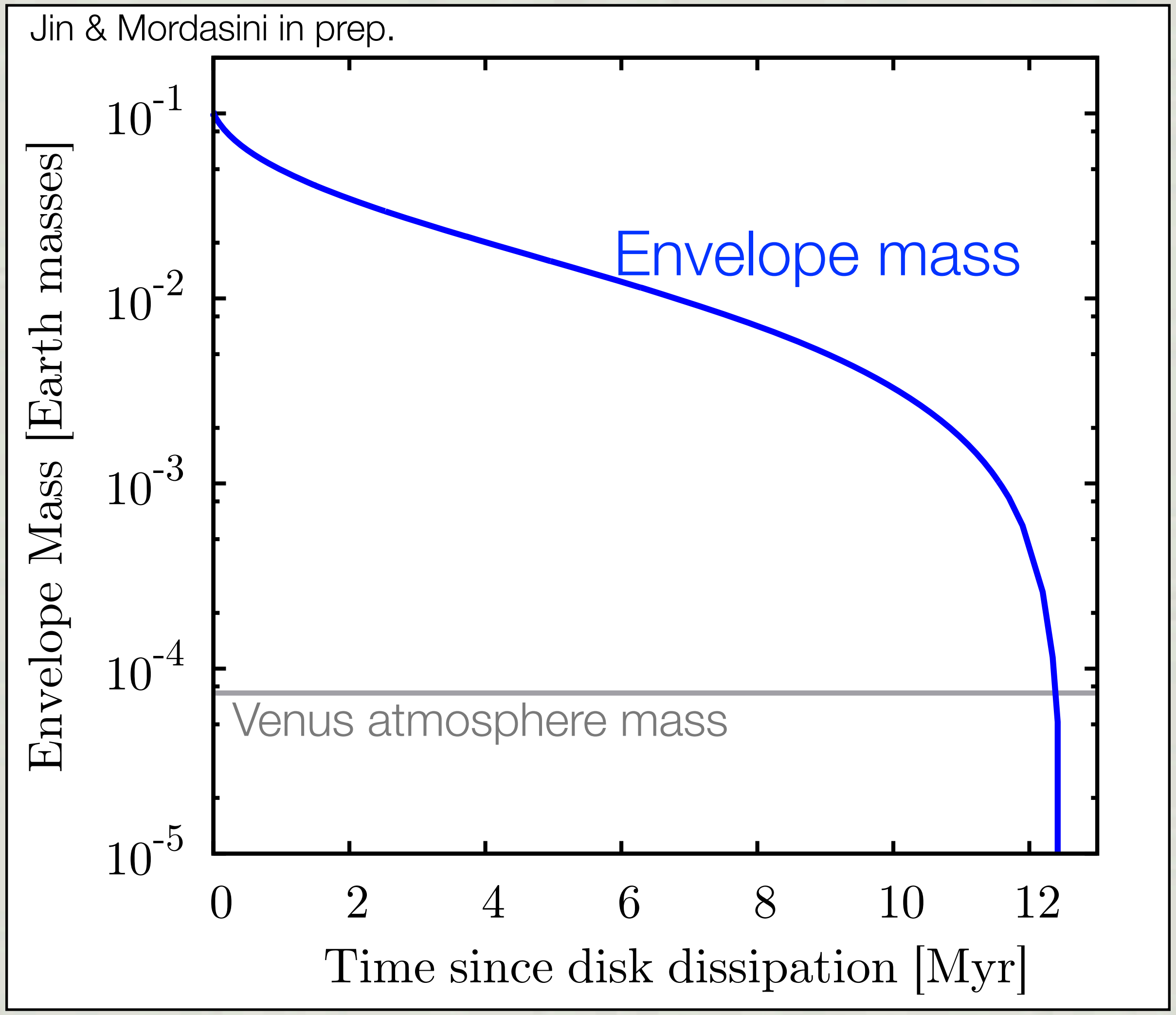
Example: Super-Earth

a=0.05 AU
M_{core}=4 M_{Earth}
M_{env}=0.1 M_{Earth}
1 M_{sun} star

L_{init}=0.1 L_J (s_0=7.5 k_b/baryon)
Earth-like core (0.33 iron, 0.66 silicate)
X-rays & EUV evaporation
Solar-composition opacity

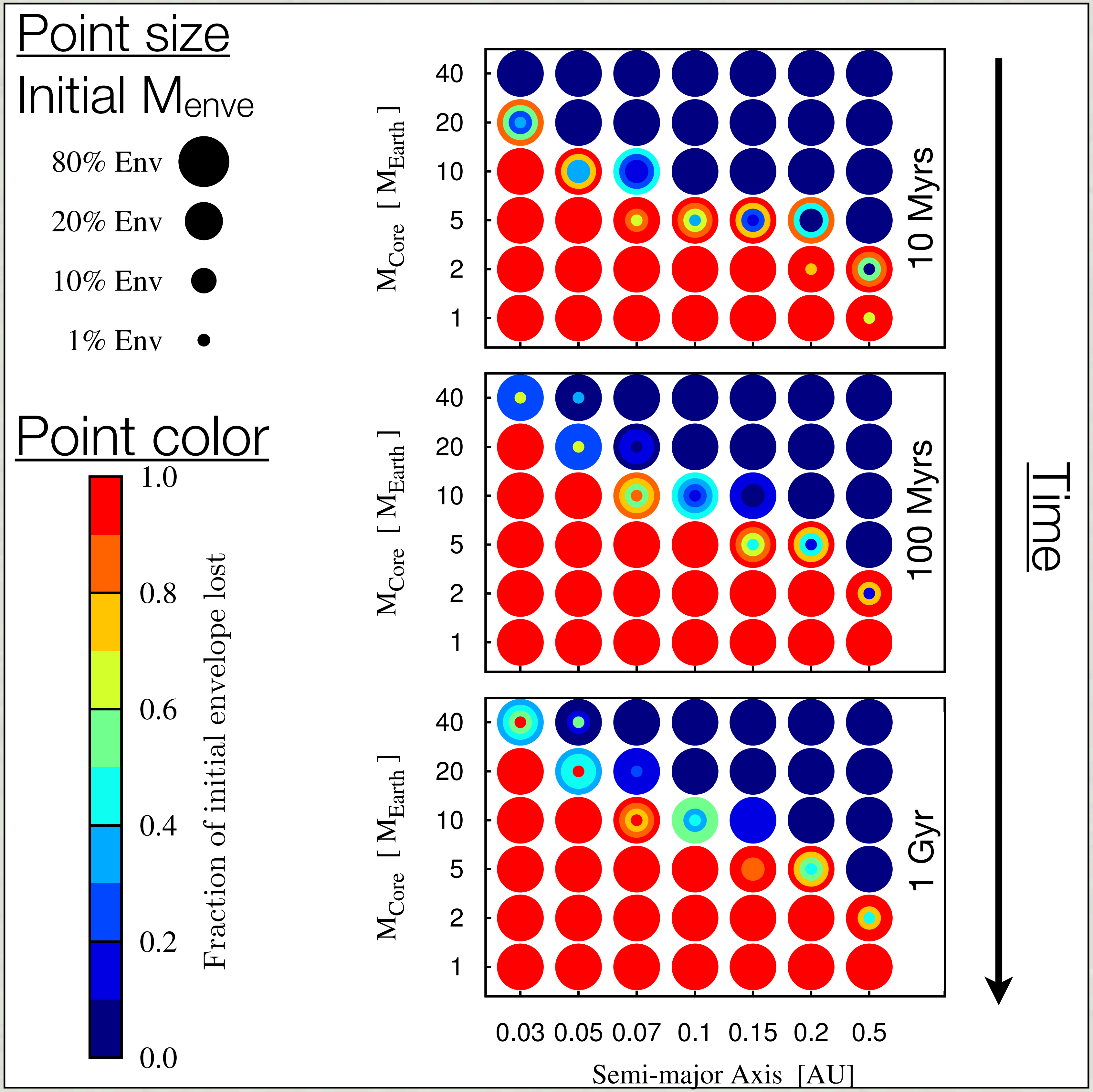
Typical M_{core}, M_{env}, L from synthesis





-completely evaporated in ~12 Myrs.
-a little bit of H/He increases the radius by a lot.
-fast decrease from ~2 R_{Earth} to R=R_{core} when envelope totally lost.

A-M-Candy diagram



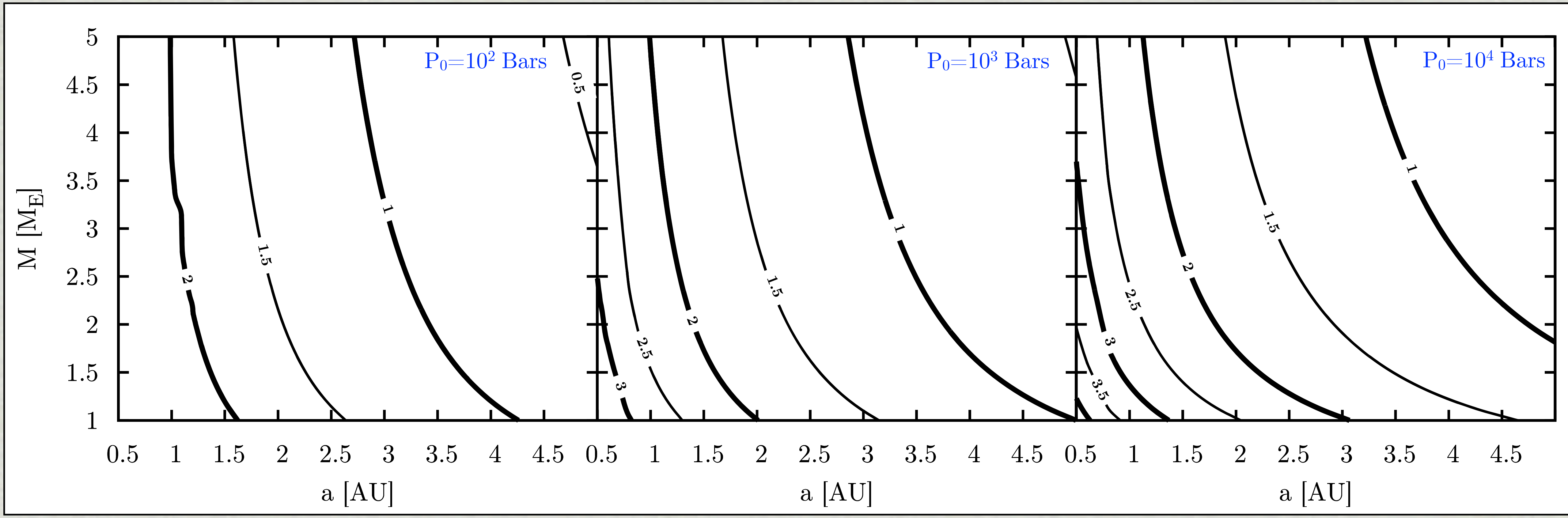
-Close-in, low-mass loose the envelope.

-Most of the action early on.

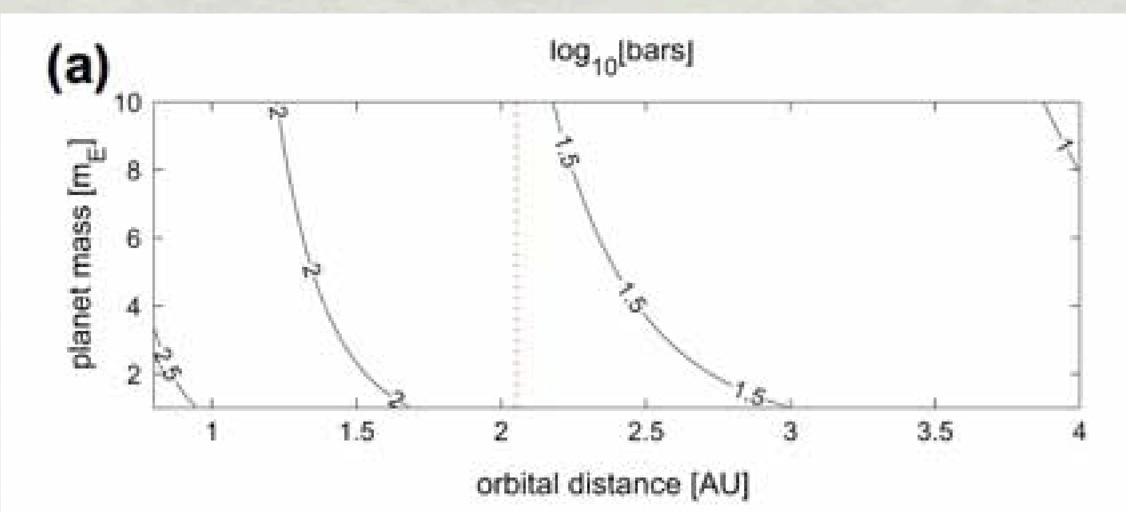
$$\tau_{\mathrm{evap}} \propto M \times \rho_{\mathrm{mean}}$$

Jin & Mordasini in prep., cf. Lopez et al. 2013

Envelope loss: comparisons

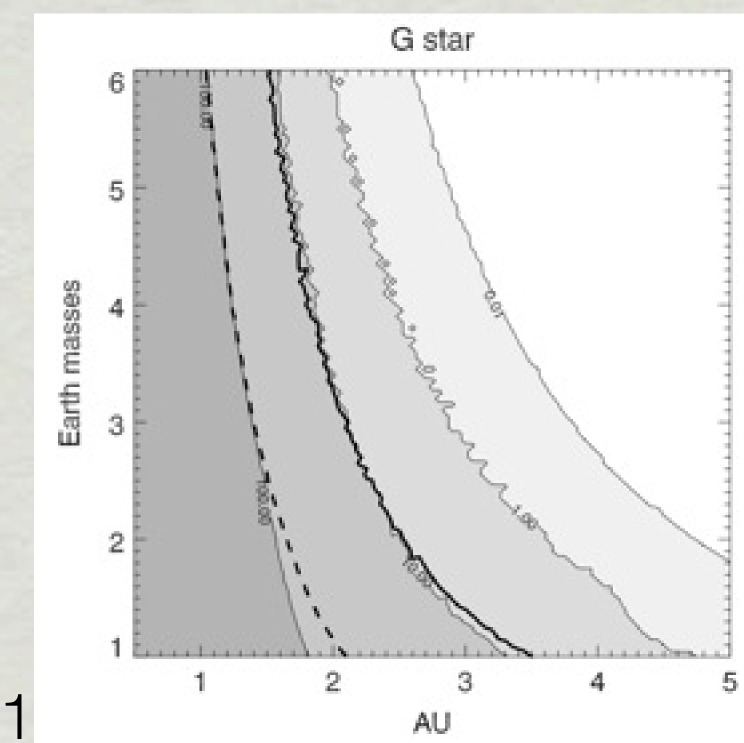


Hydrodynamic escape assumption

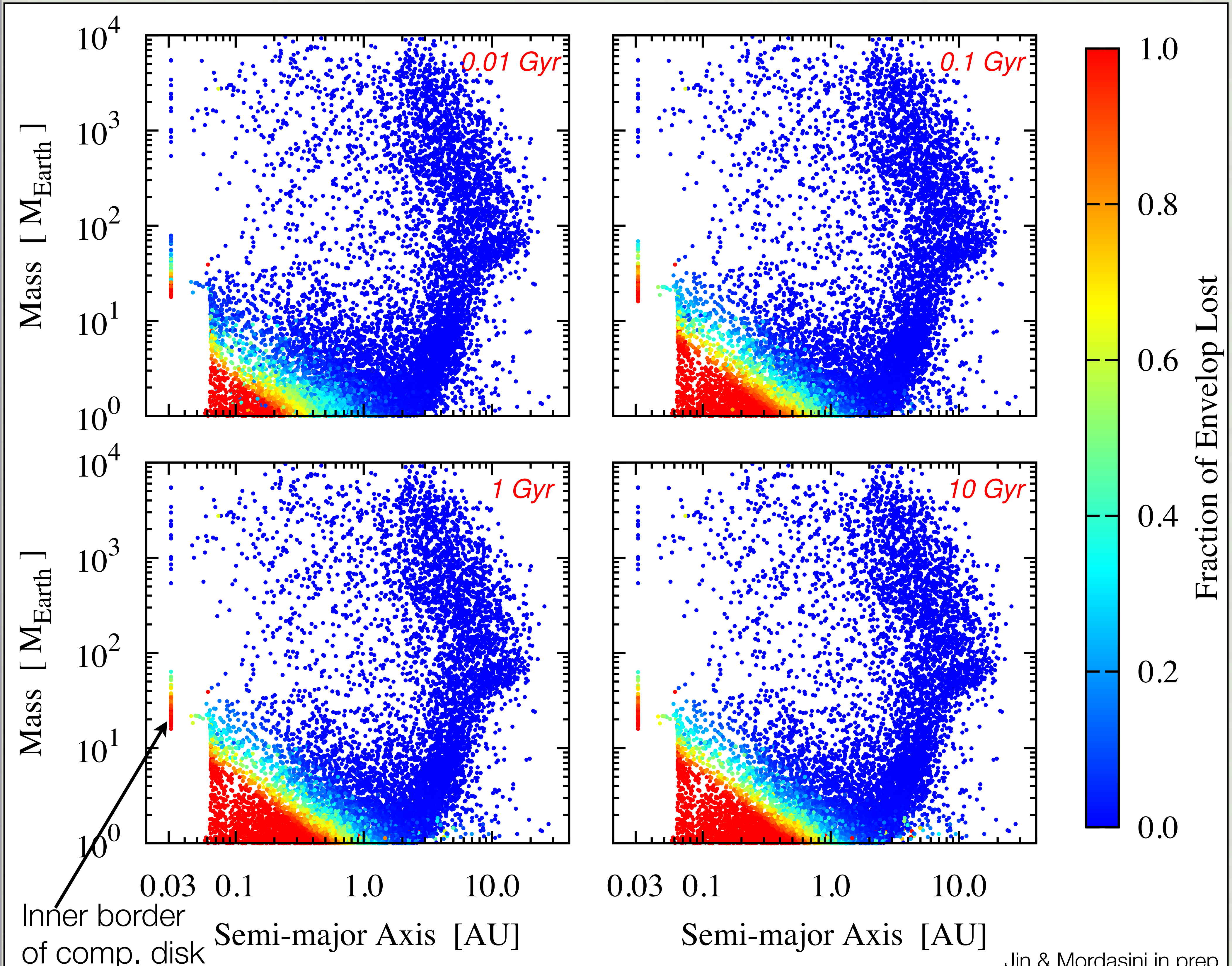


Wordsworth 2012

Pierrehumbert & Gaidos 2011



Temporal evolution a-M w. escape



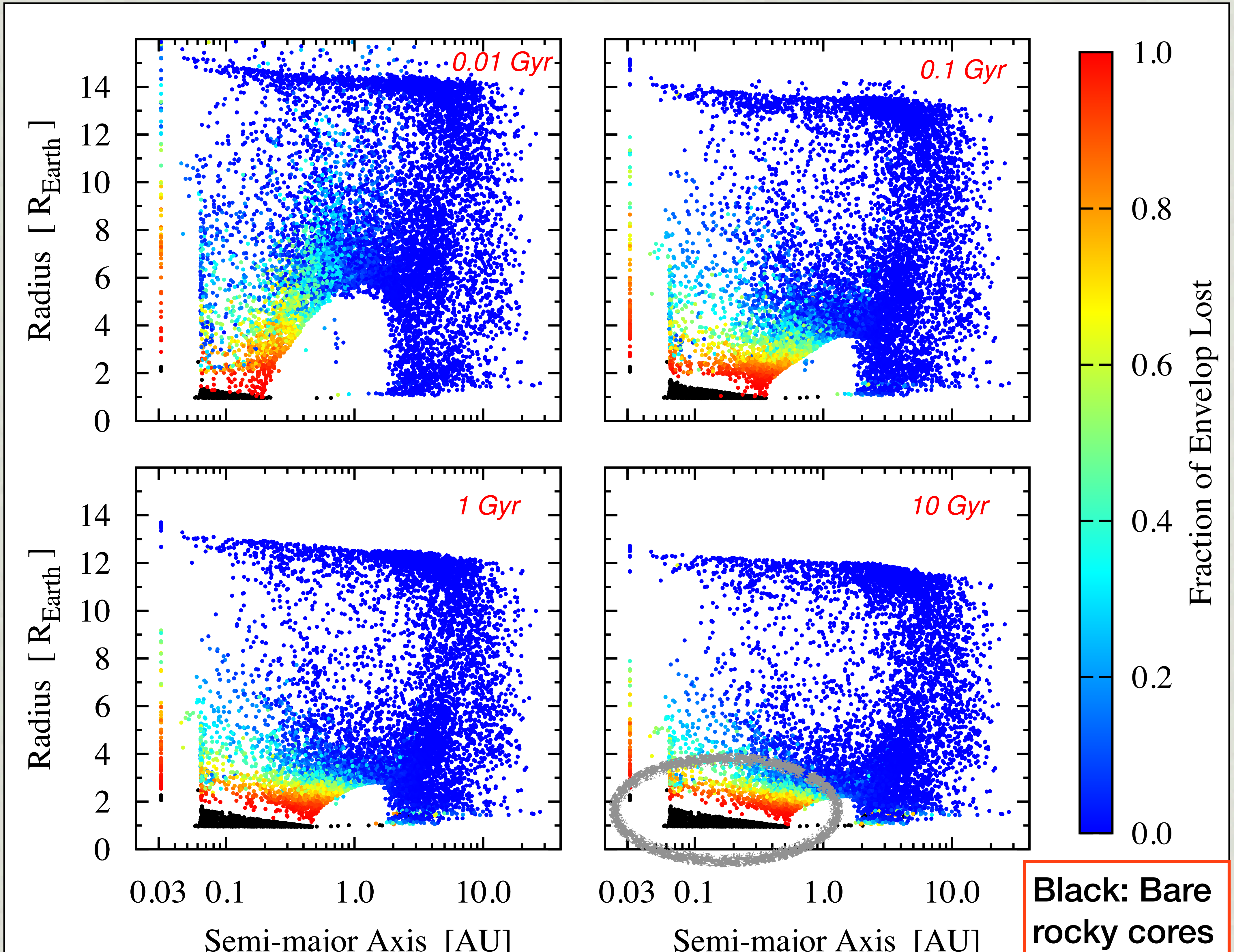
-Close-in, low-mass loose the envelope.
-Most of the action early on.

a-M does not change much. (a>0.06 AU):
-Giants don't loose much.
-low M planets have $M_{env} << M_{core}$

Earth?

M_{star}=1 M_{sun}, isothermal type I migration rate x 0.1, cold accretion. 1 embryo/disk, no special inflation mechanisms.

Temporal evolution a-R w. escape

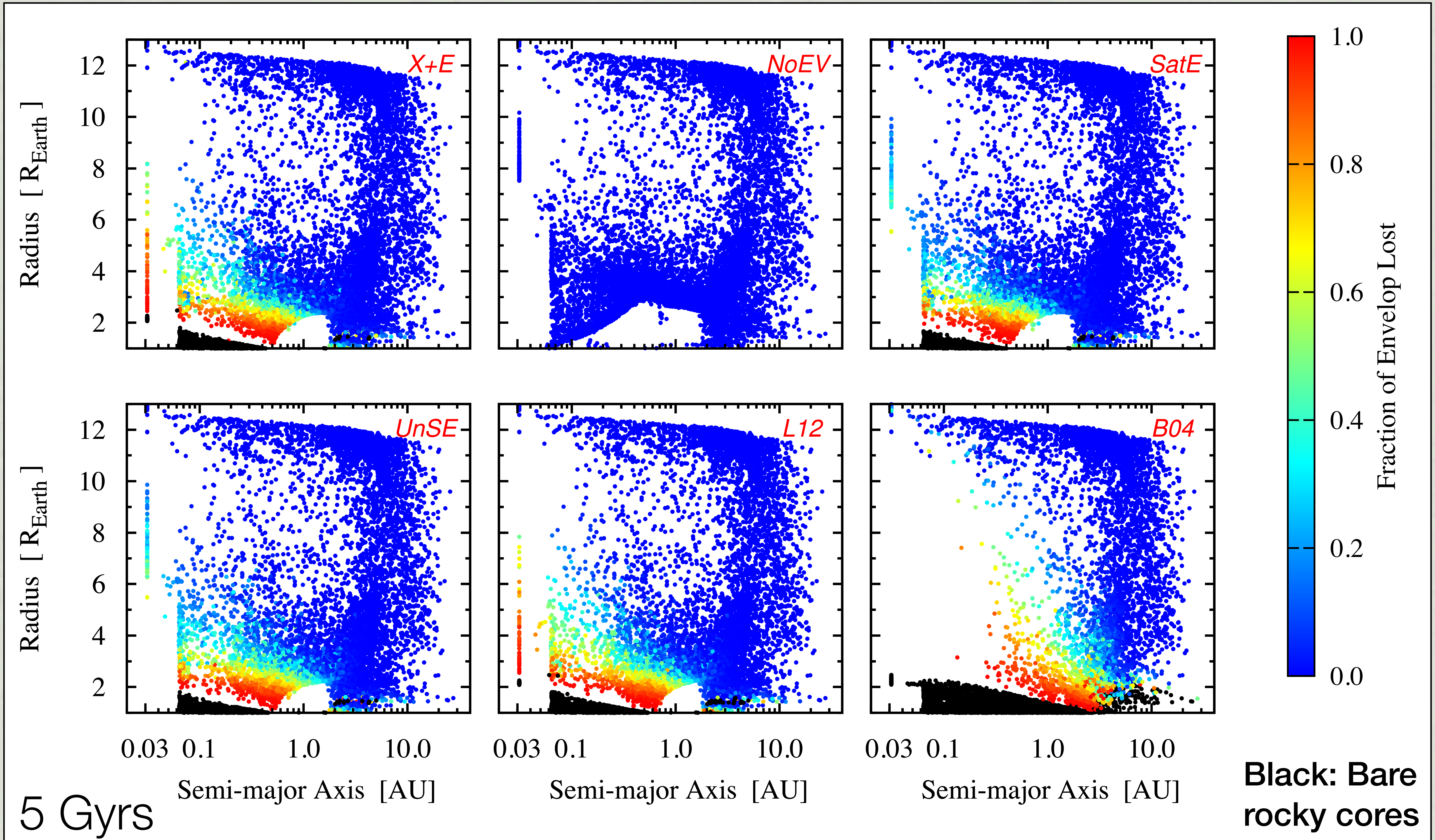


a-R does change!

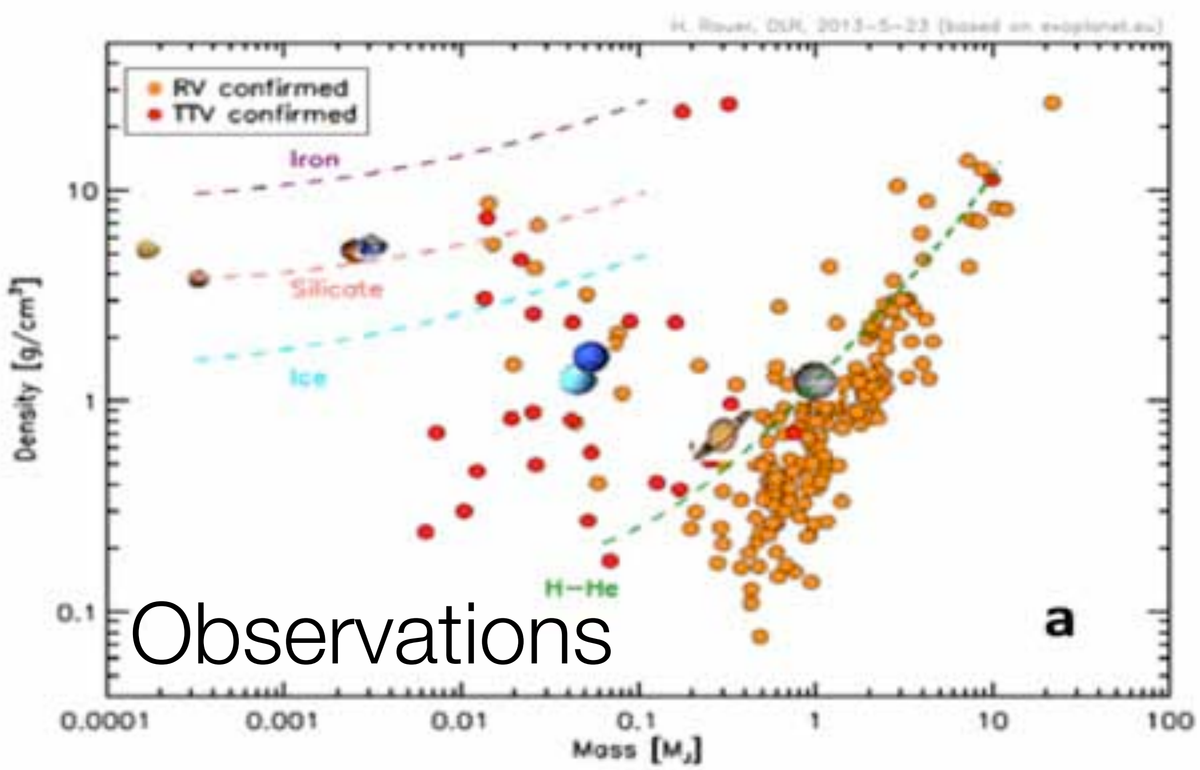
Depleted strip at ~2 R_{Earth}

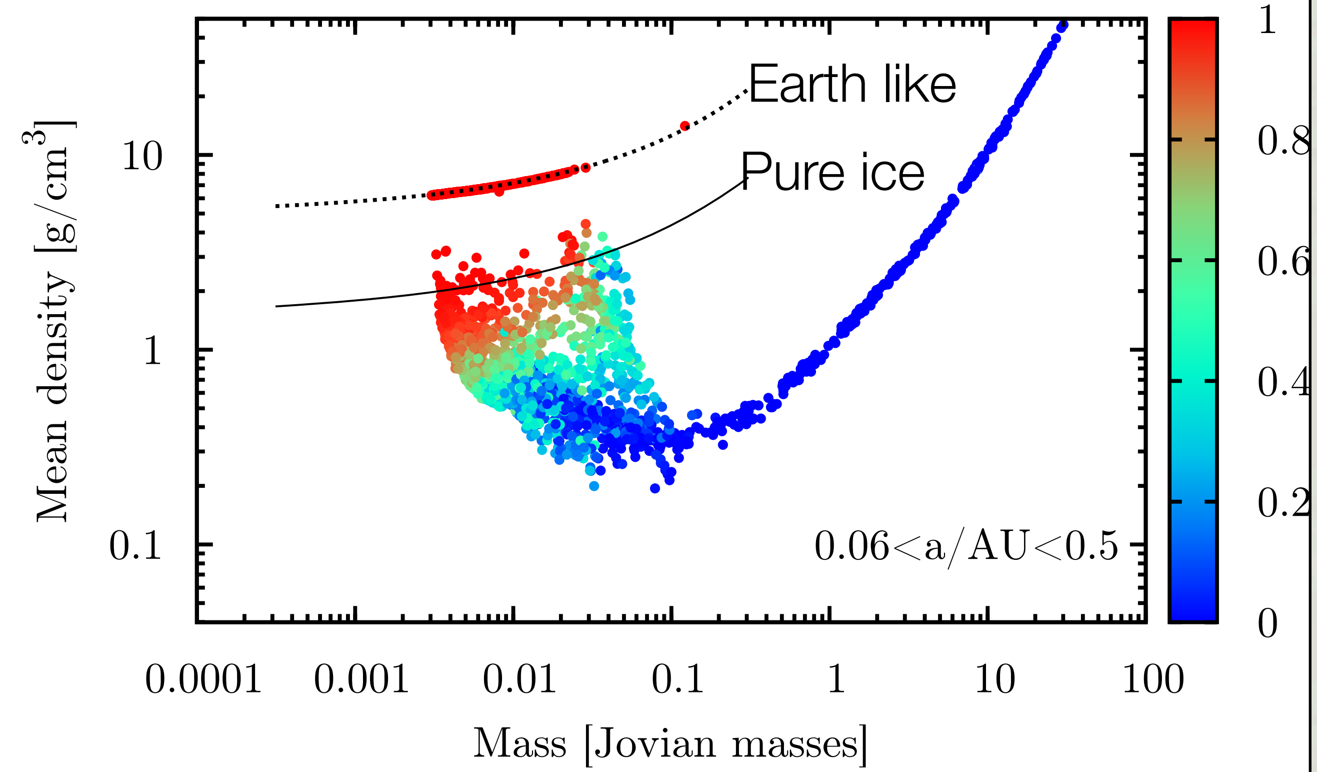
M_{star}=1 M_{sun} Isothermal Type I rate x 0.1. Cold accretion. 1 embryo/disk, no special inflation mechanisms.

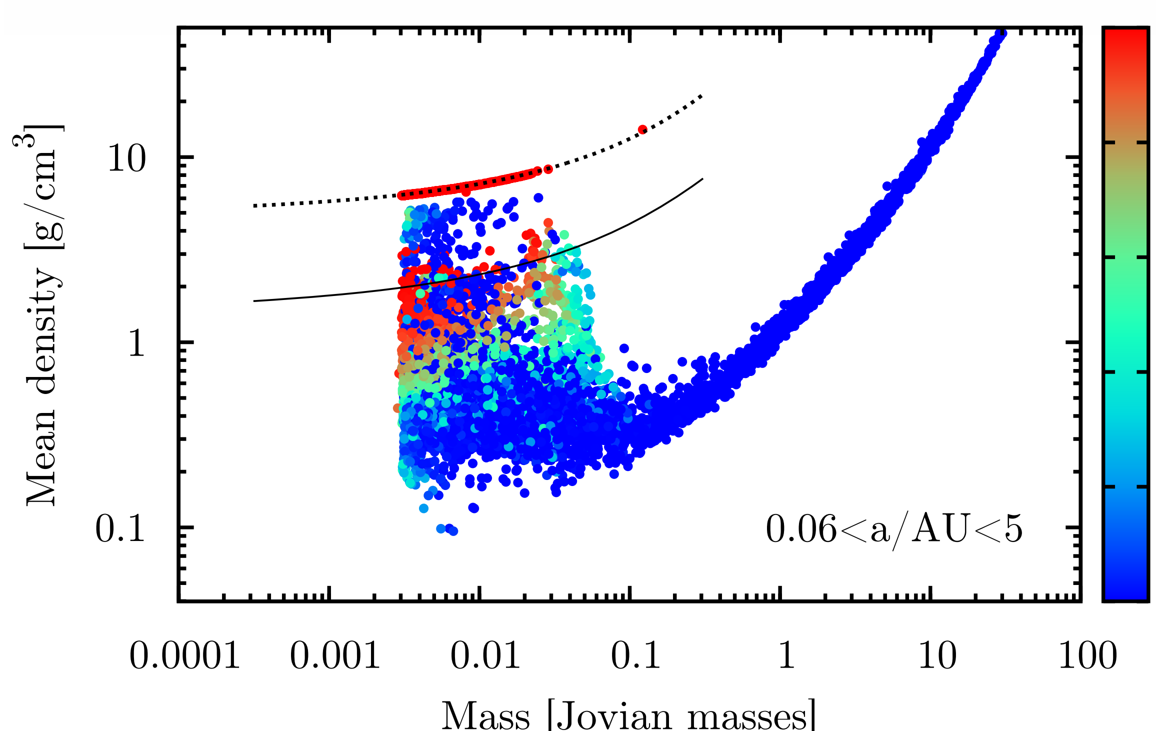
Impact model assumptions

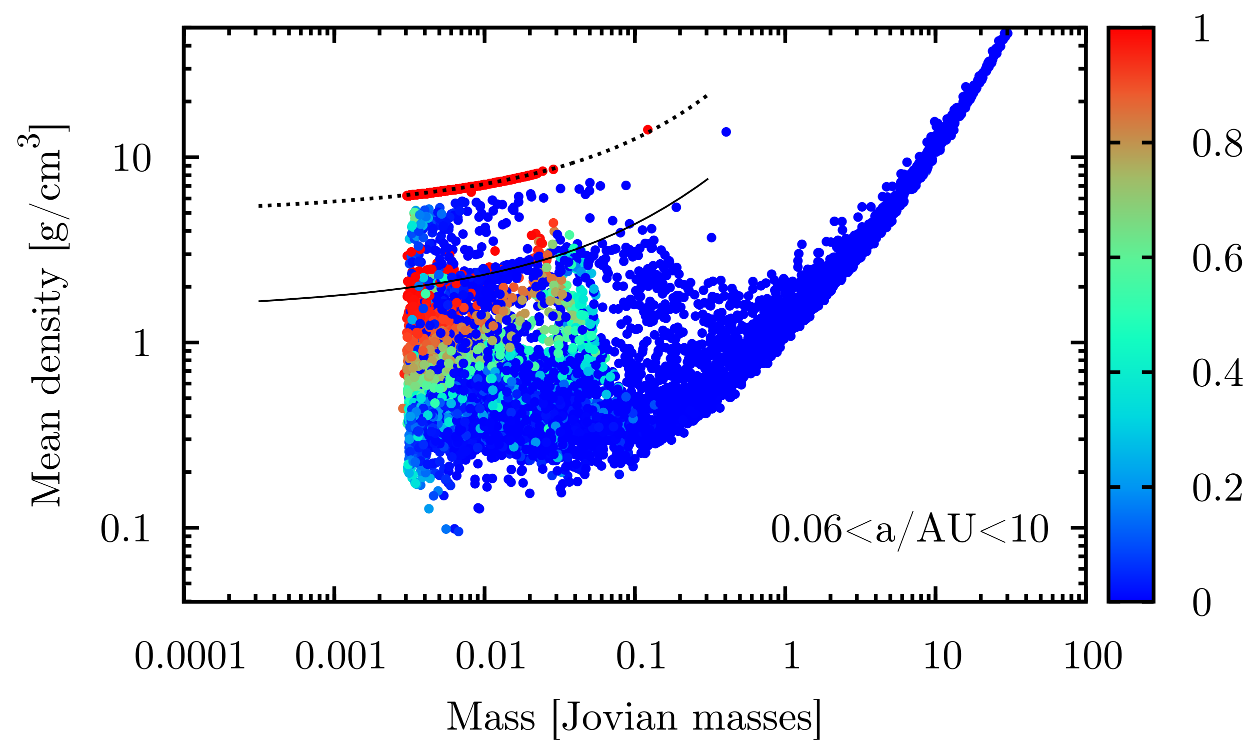


Mass-density





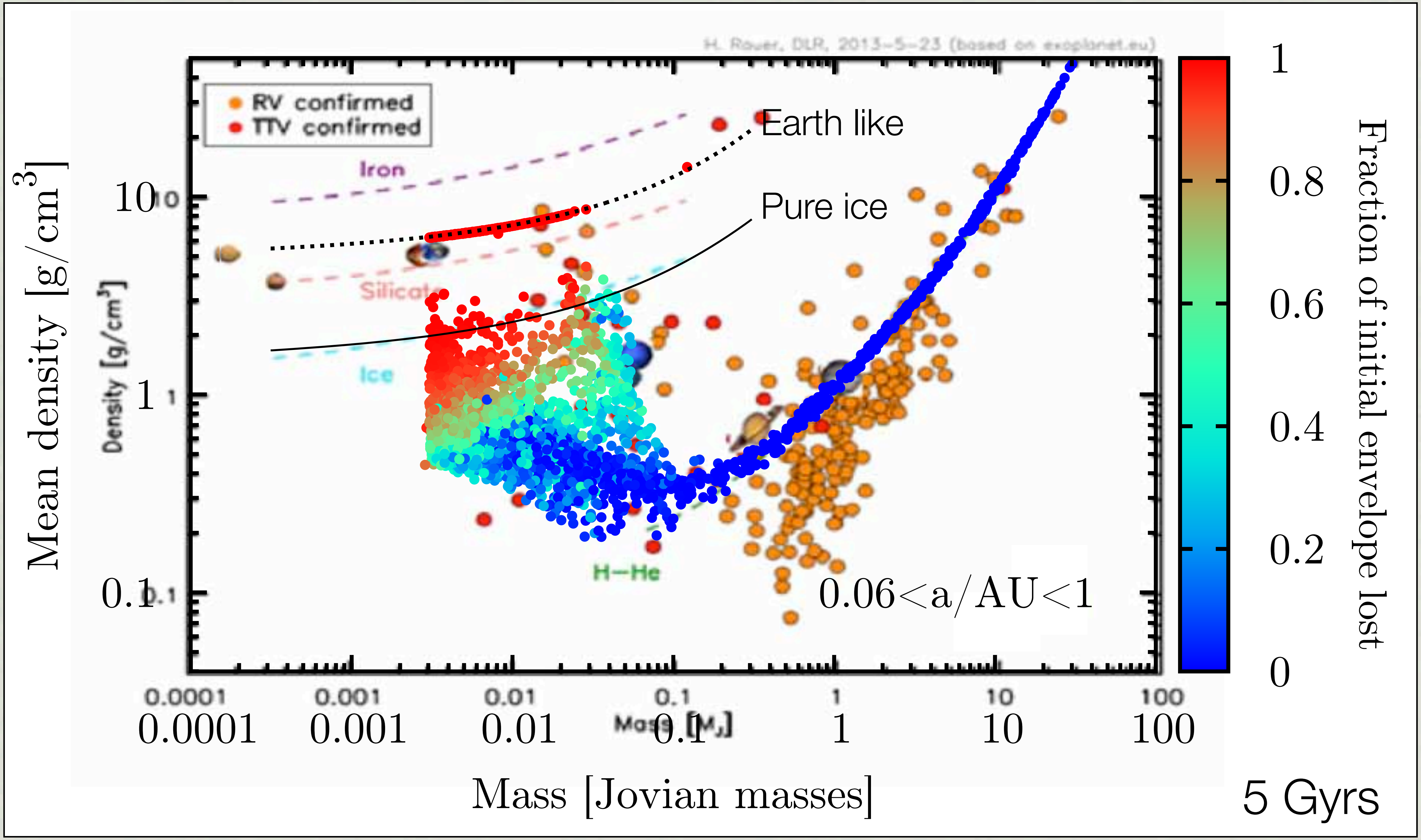




Empty if close-in low-mass planets are rocky
Filled if close-in low-mass planets are icy

Synthetic

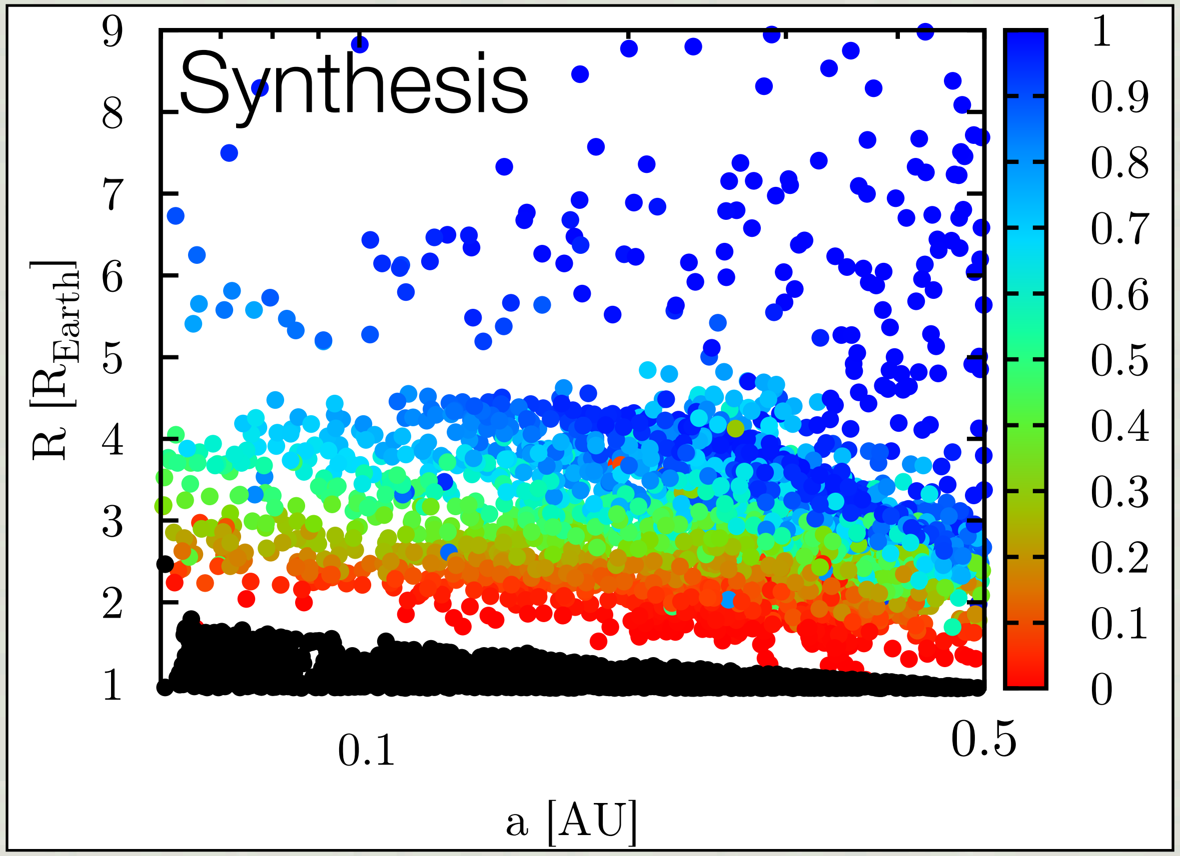
Mass-density relation

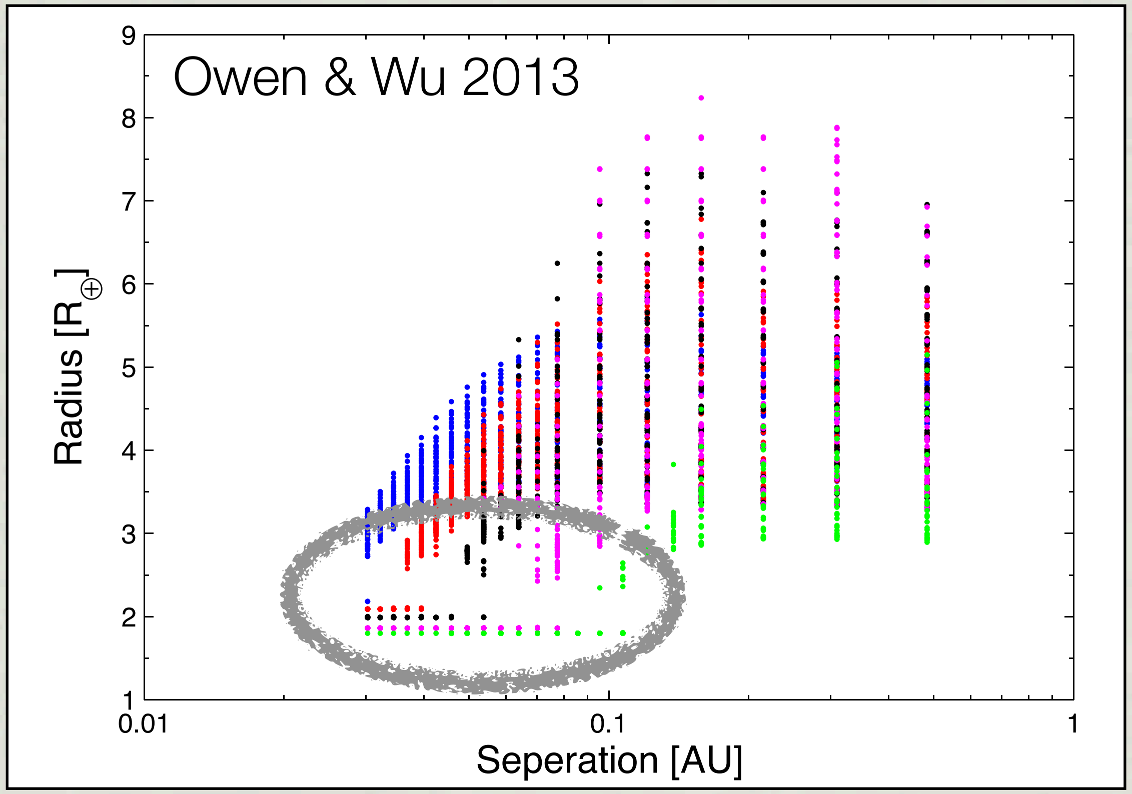


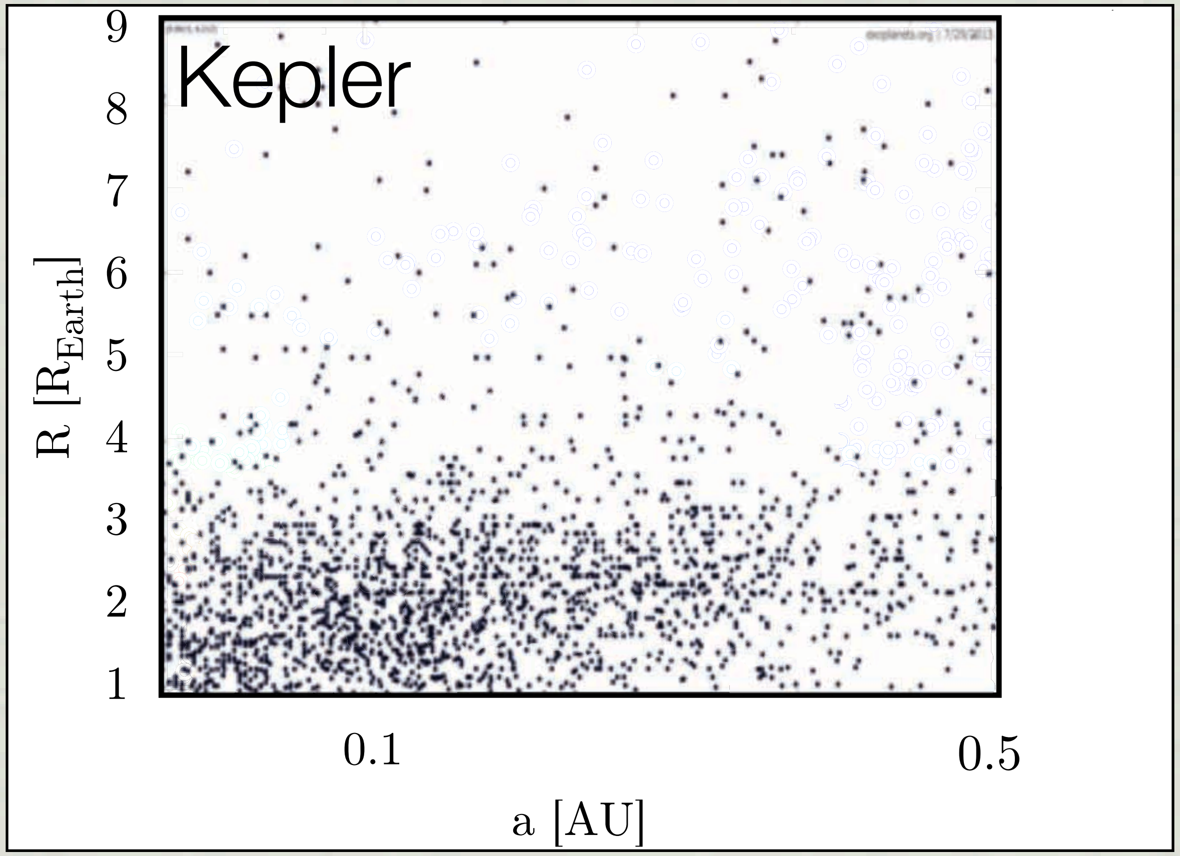
Empty if close-in low-mass planets are rocky
Filled if close-in low-mass planets are icy

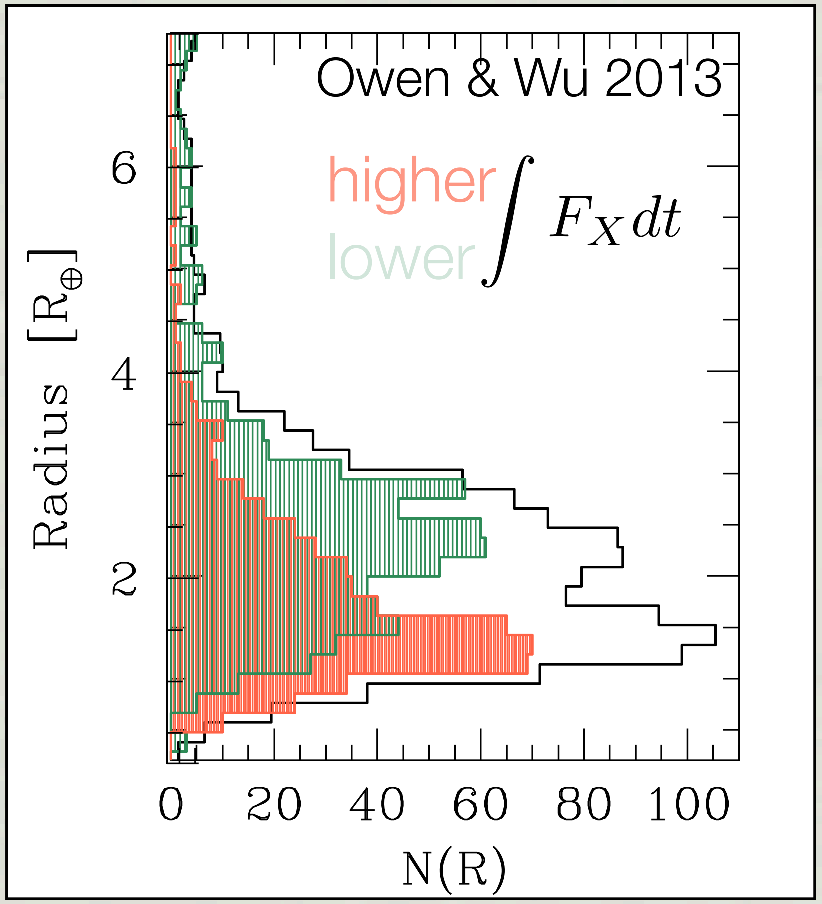
Migration models!

Comparison with Kepler









need longer baseline

Conclusions

- PLATO as a large survey with well defined detection bias yields quantitative statistical observational constraints that are crucial for planet formation and evolution theory.
- Mass-radius (or mass-density) diagram is an observational result that contains information on several key processes: envelope accretion and loss, orbital migration, inflation...
  - Exoplanets show a large diversity. To still see the global trends (i.e., the fundamental physical processes), many very well defined M-R measurements are necessary.
  - Large numbers are also necessary because what we really want is a M-R-a-M_{star}-[Fe/H]-t relation.

Thanks!