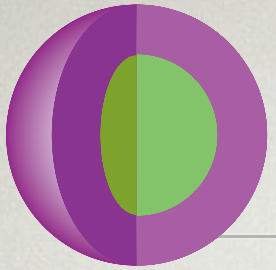
31st International Colloquium of the Institut d'Astrophysique de Paris
From Super-Earths to Brown Dwarfs: Who's who?
25-29 August 2014, ISSI-Beijing

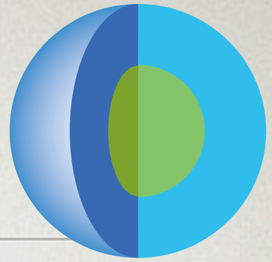
Theoretical Perspectives on Super-Earths and Mini-Neptunes with a focus on Origins and Compositions of Short-Period Planets

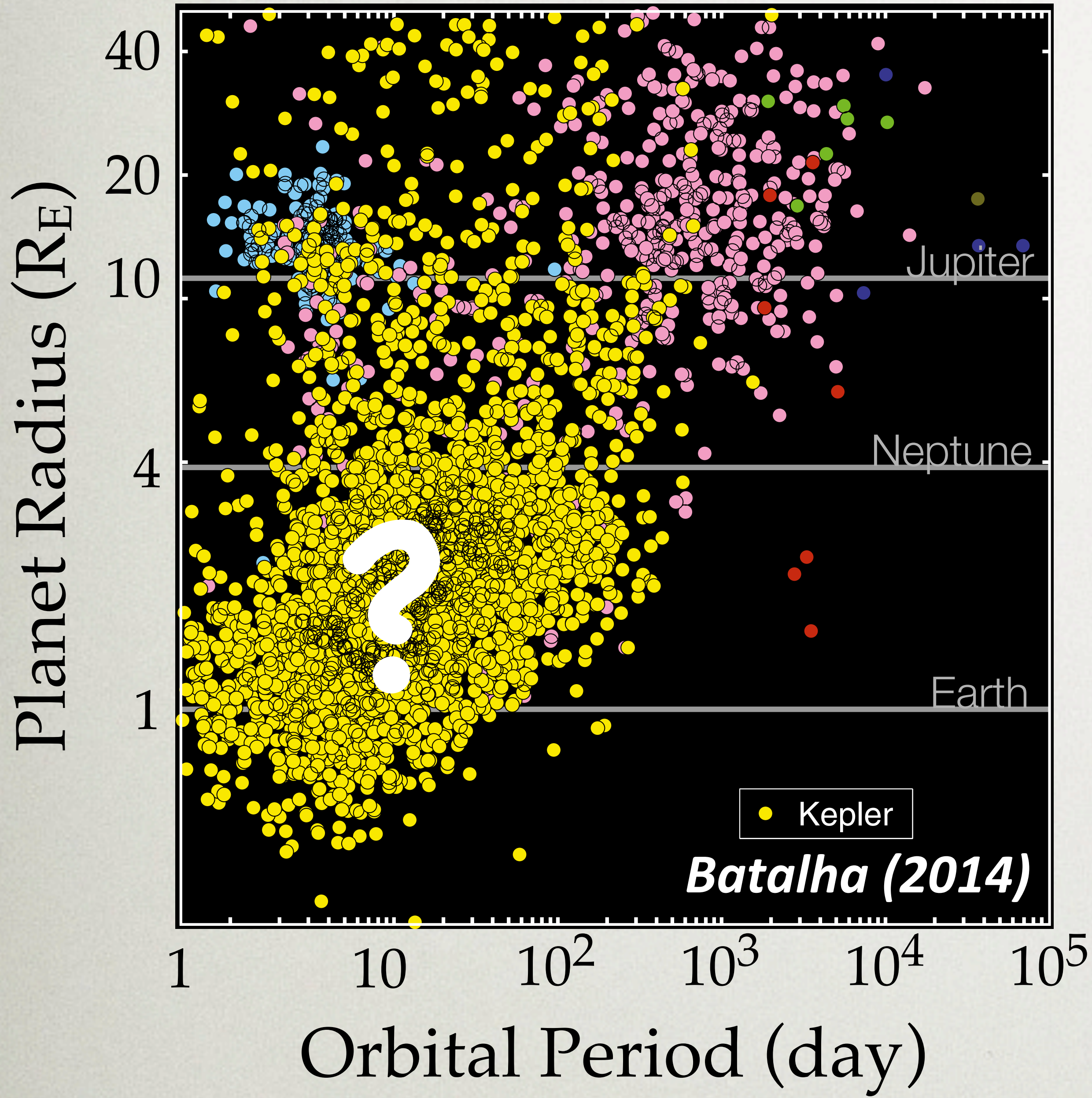
Masahiro IKOMA

Department of Earth Planetary Science
THE UNIVERSITY OF TOKYO

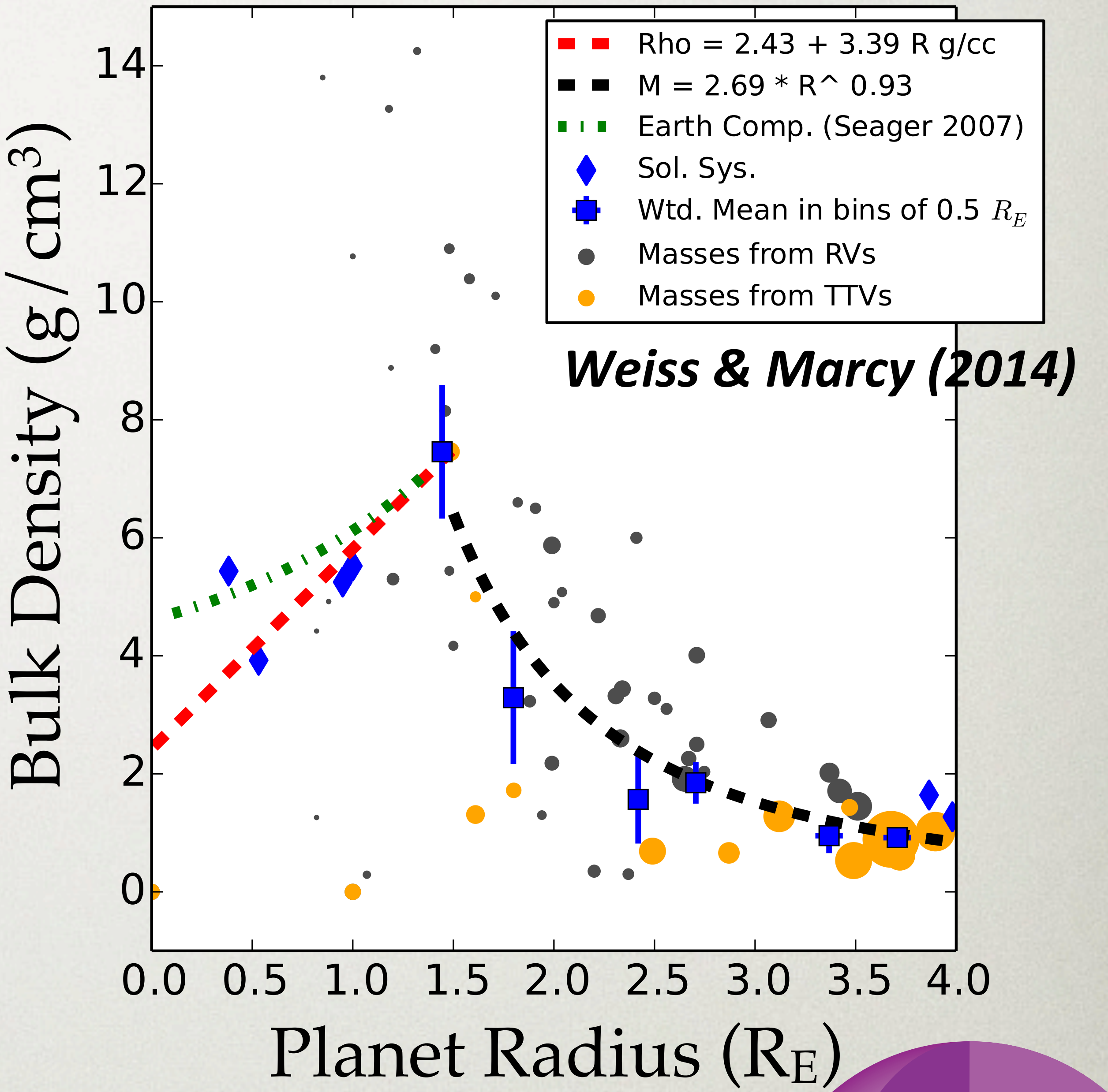


Who’s who?



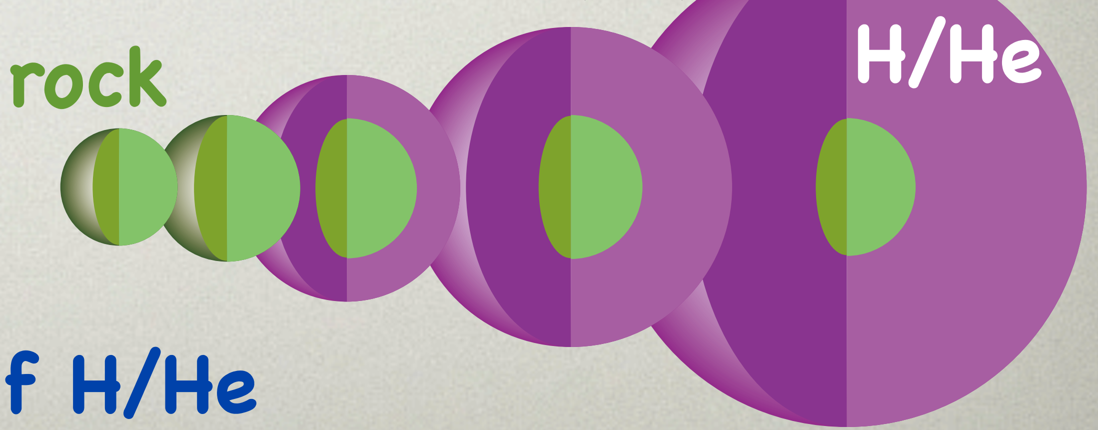


Batalha (2014)



Weiss & Marcy (2014)

- Are the intermediate planets (IPs) super-Earths or mini-Neptunes?
- A simple explanation is that IPs are rocky cores with different amounts of H/He

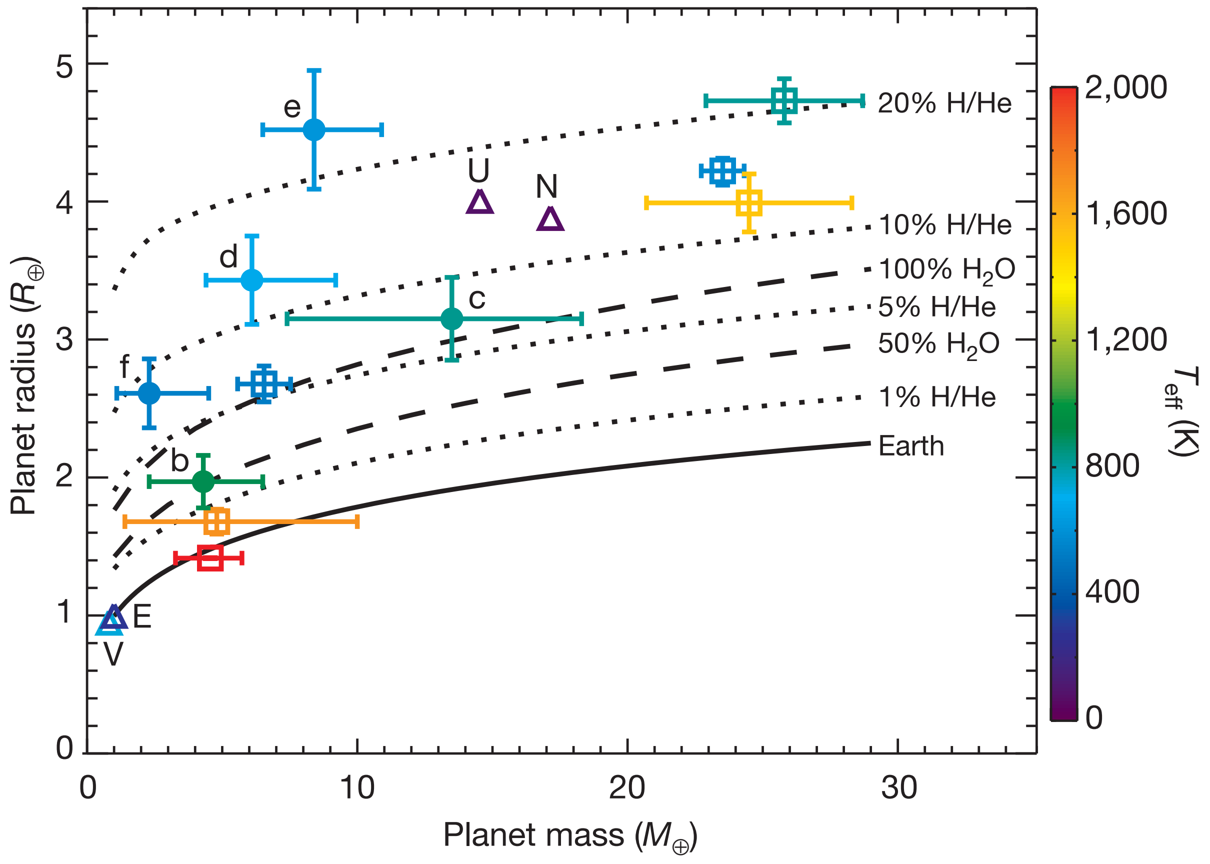


Low-Density Low-Mass Planets

doi:10.1038/nature09760

A closely packed system of low-mass, low-density planets transiting Kepler-11

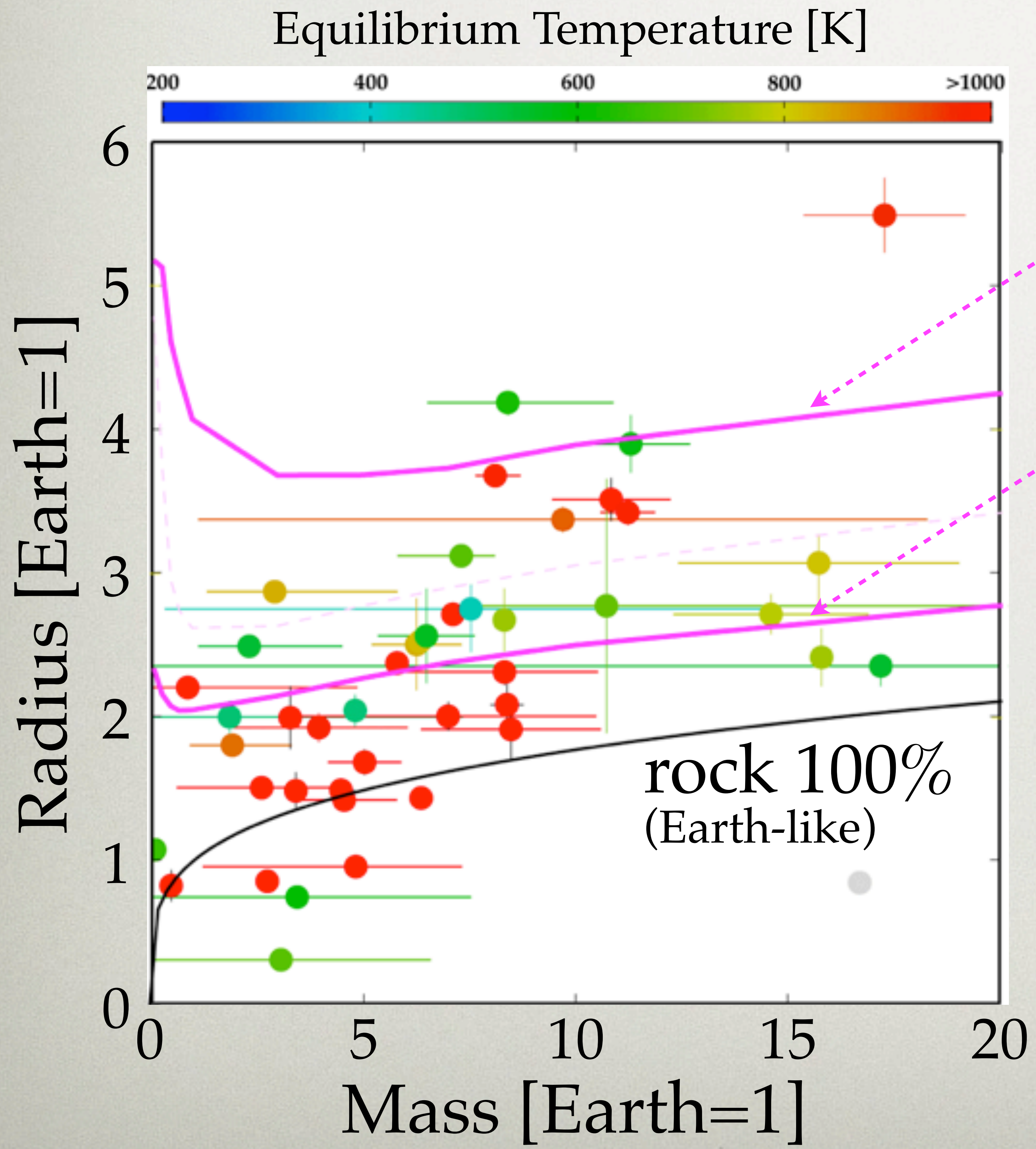
Jack J. Lissauer[1], Daniel C. Fabrycky[2], Eric B. Ford[3], William J. Borucki[1], Francois Fressin[4], Geoffrey W. Marcy[5], Jerome A. Orosz[6], Jason F. Rowe[7], Guillermo Torres[4], William F. Welsh[6], Natalie M. Batalha[8], Stephen T. Bryson[1], Lars A. Buchhave[9], Douglas A. Caldwell[7], Joshua A. Carter[4], David Charbonneau[4], Jessie L. Christiansen[7], William D. Cochran[10], Jean-Michel Desert[4], Edward W. Dunham[11], Michael N. Fanelli[12], Jonathan J. Fortney[2], Thomas N. Gautier III[13], John C. Geary[4], Ronald L. Gilliland[14], Michael R. Haas[1], Jennifer R. Hall[15], Matthew J. Holman[4], David G. Koch[1], David W. Latham[4], Eric Lopez[2], Sean McCauliff[15], Neil Miller[2], Robert C. Morehead[3], Elisa V. Quintana[7], Darin Ragozzine[4], Dimitar Sasselov[4], Donald R. Short[6] & Jason H. Steffen[16]



- Five low-mass planets around a Sun-like star
- All the low-mass planets are less dense than rocky objects

Low-Density Low-Mass Planets

Observed mass-radius relationship (data from exoplanets.org)

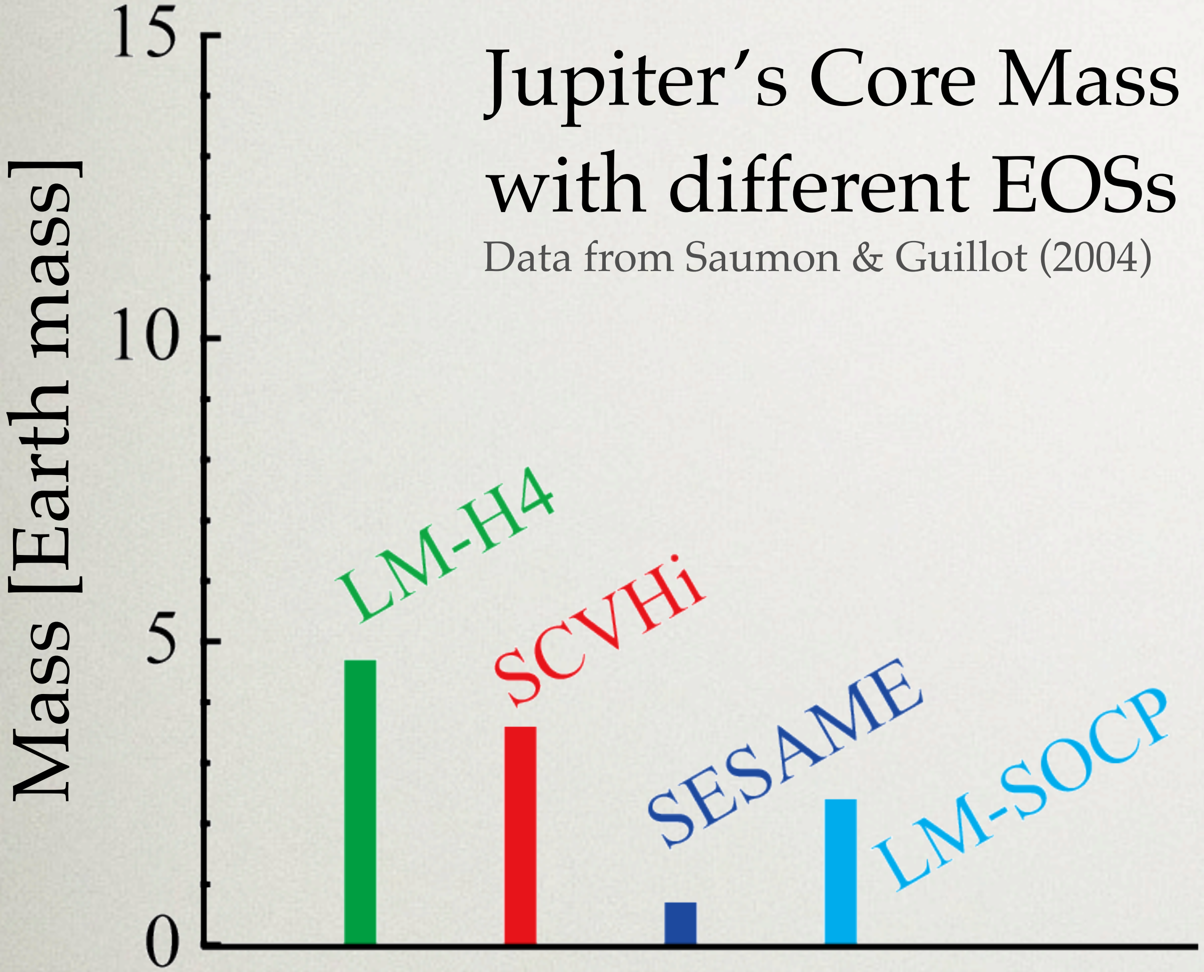


Theoretical line for
H/He 10% +rock 90%

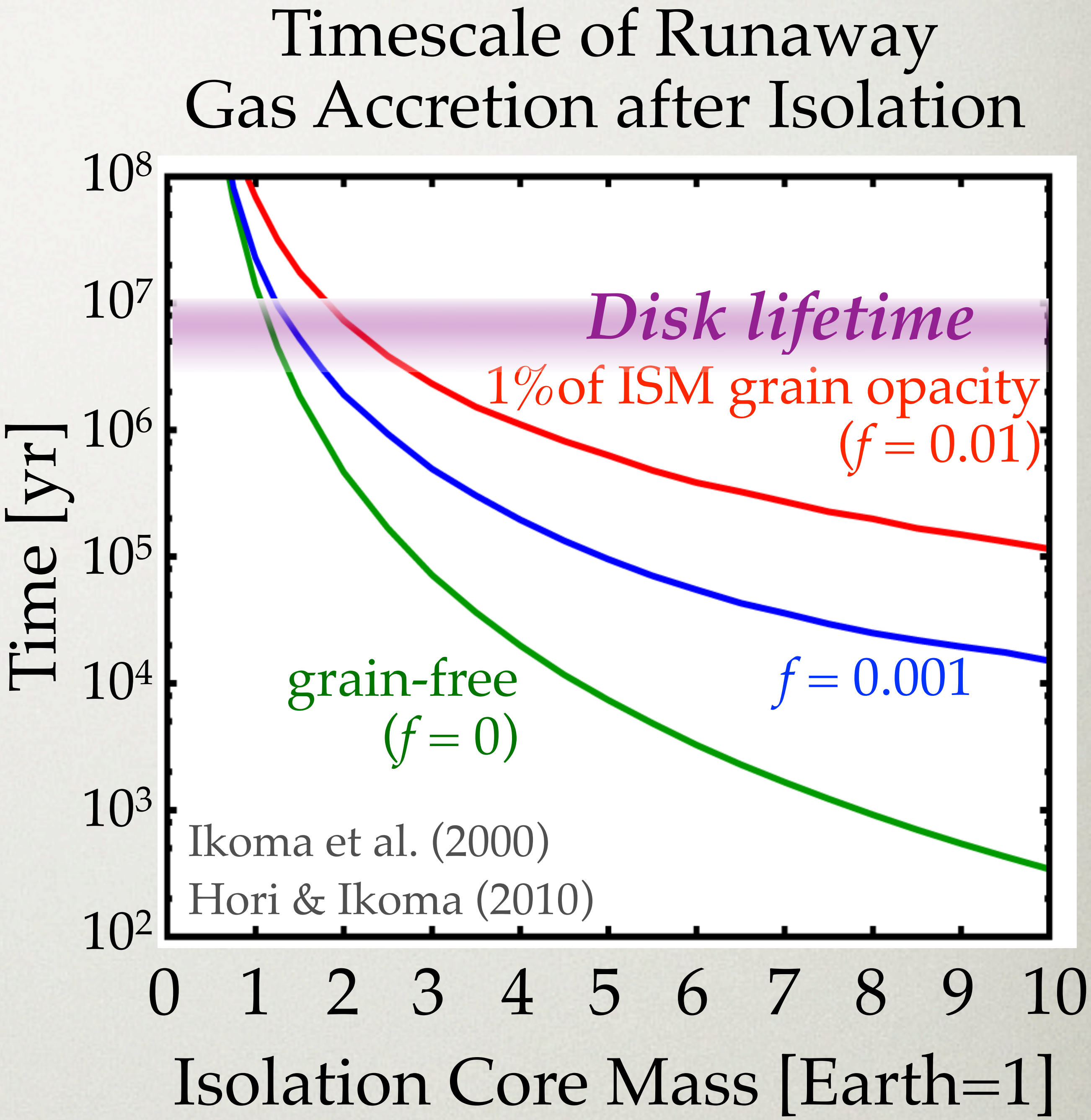
Theoretical line for
H/He 1% +rock 99%

- **Low-mass exoplanets with short periods are so diverse in bulk composition**
- Provided the large radii are due to the presence of H/He atmospheres, **the fraction of H/He atmospheres ranges up to ~10% of total planet mass**

Jupiter's Small Core Problem



Jupiter's core is as small as
< 5 Earth masses !
→ super-Earth mass



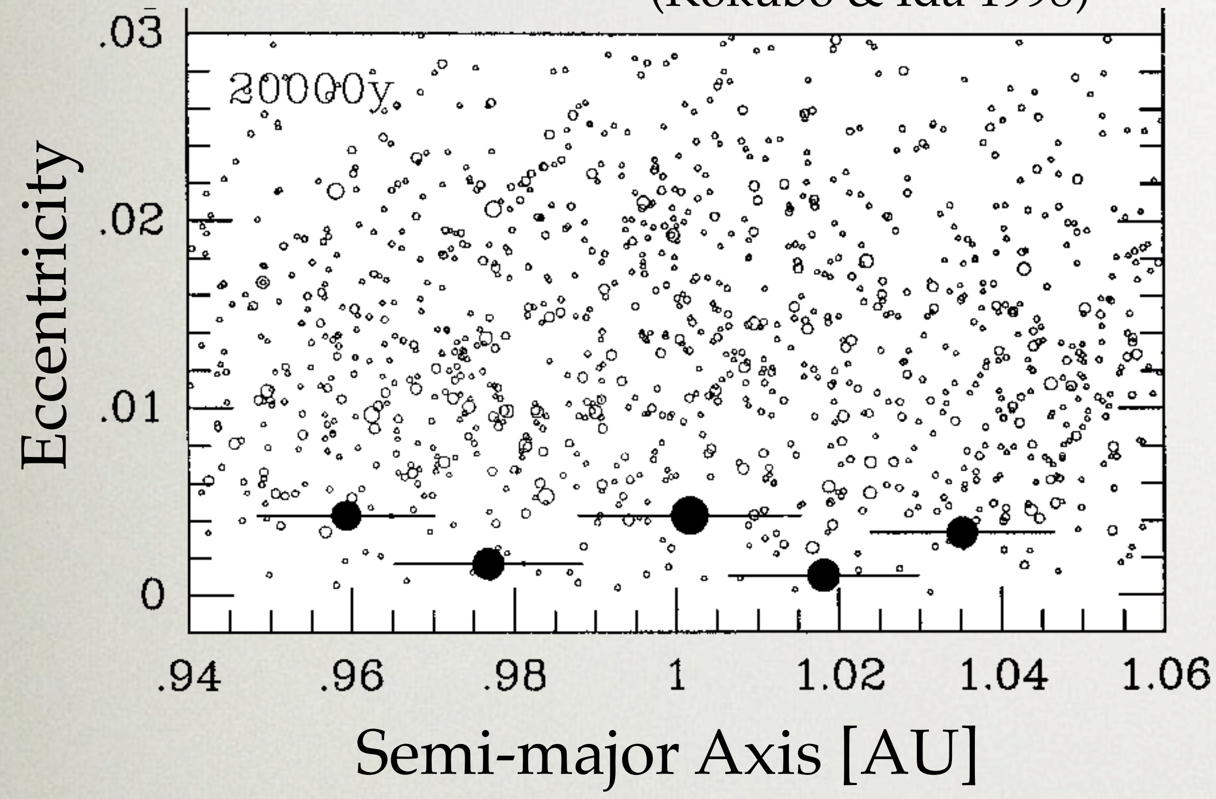
**Super-Earth mass is large enough
for a core to be a gas giant.**

Relevant Processes

Solid Accretion

Result of *N*-body simulation

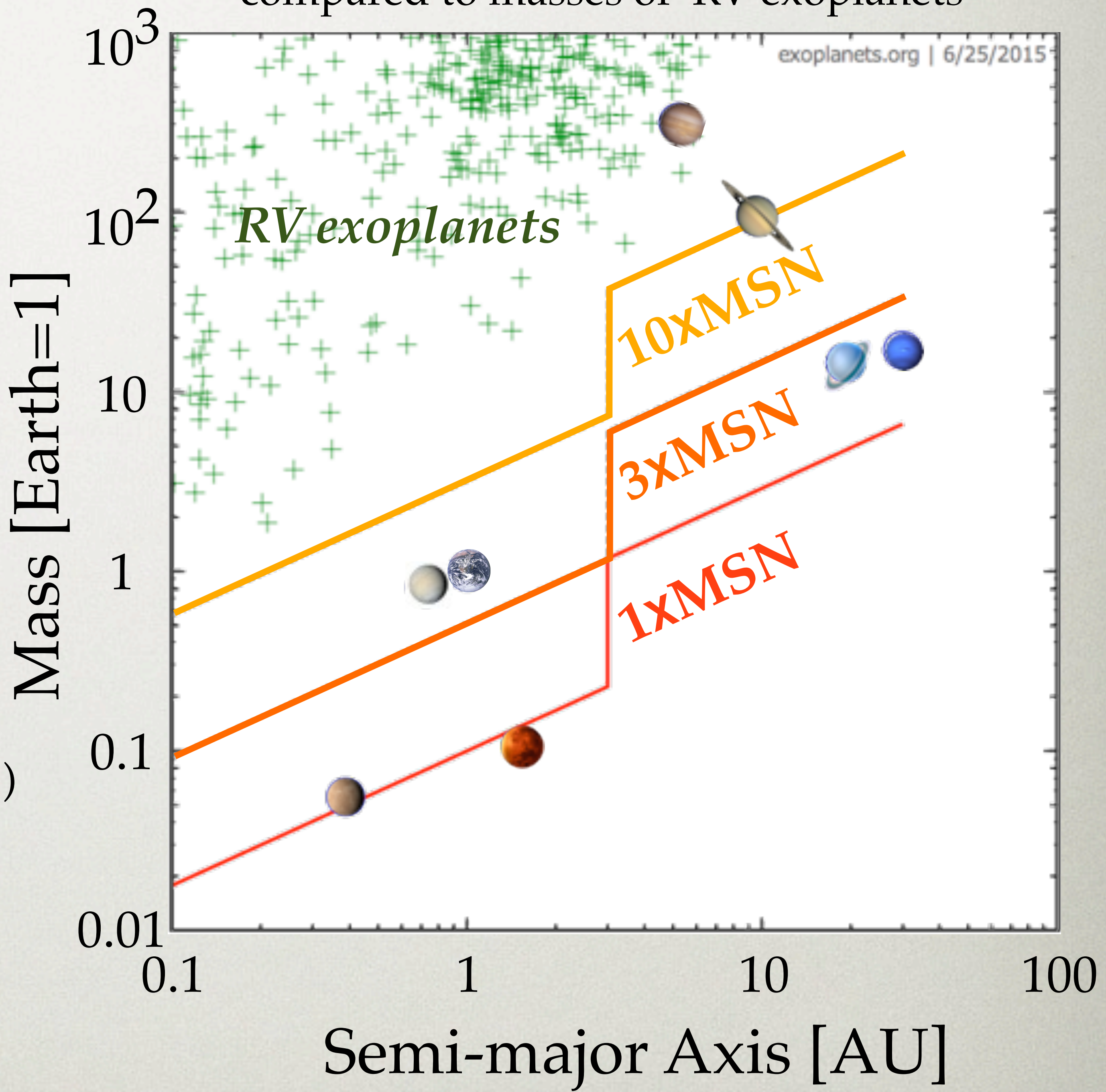
(Kokubo & Ida 1998)



Planetary embryos become isolated (Lissauer 1987; Kokubo & Ida 1998)

Isolation Mass

compared to masses of RV exoplanets



- Local accretion is unable to form super-Earth-mass cores.
- **Have to collect solids from wider regions.**

=> Need for orbital migration and/or giant collision

Dilemma

- Orbital migration of low-mass planets requires the presence of disk gas.
- If a super-Earth-mass core is formed and isolated well before disk dispersal, the core readily becomes a gas giant.

Why are there so many close-in super-Earth-mass planets?

Relevant Processes

Disk Dissipation

Two-Step (UV-switch) Model

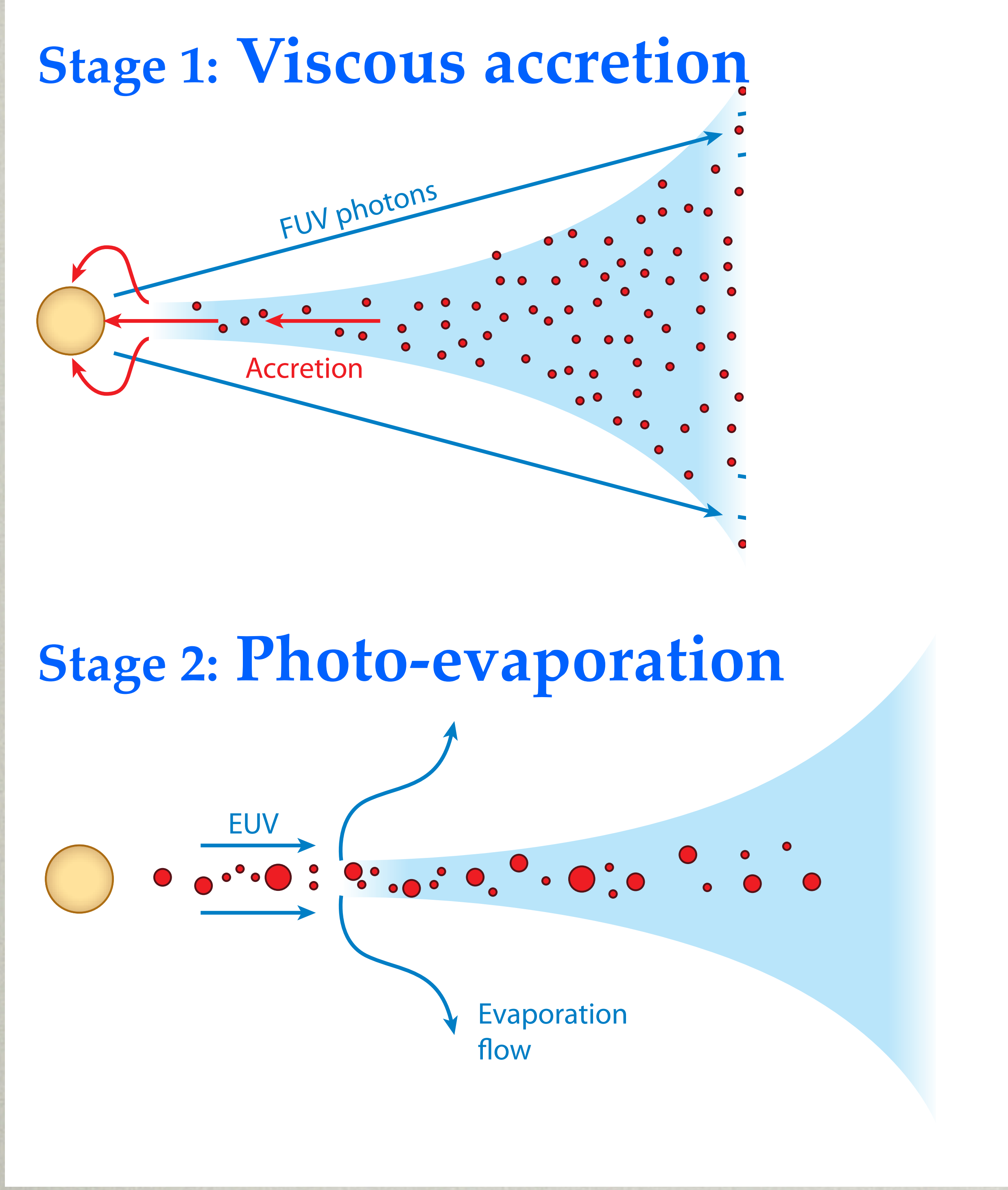
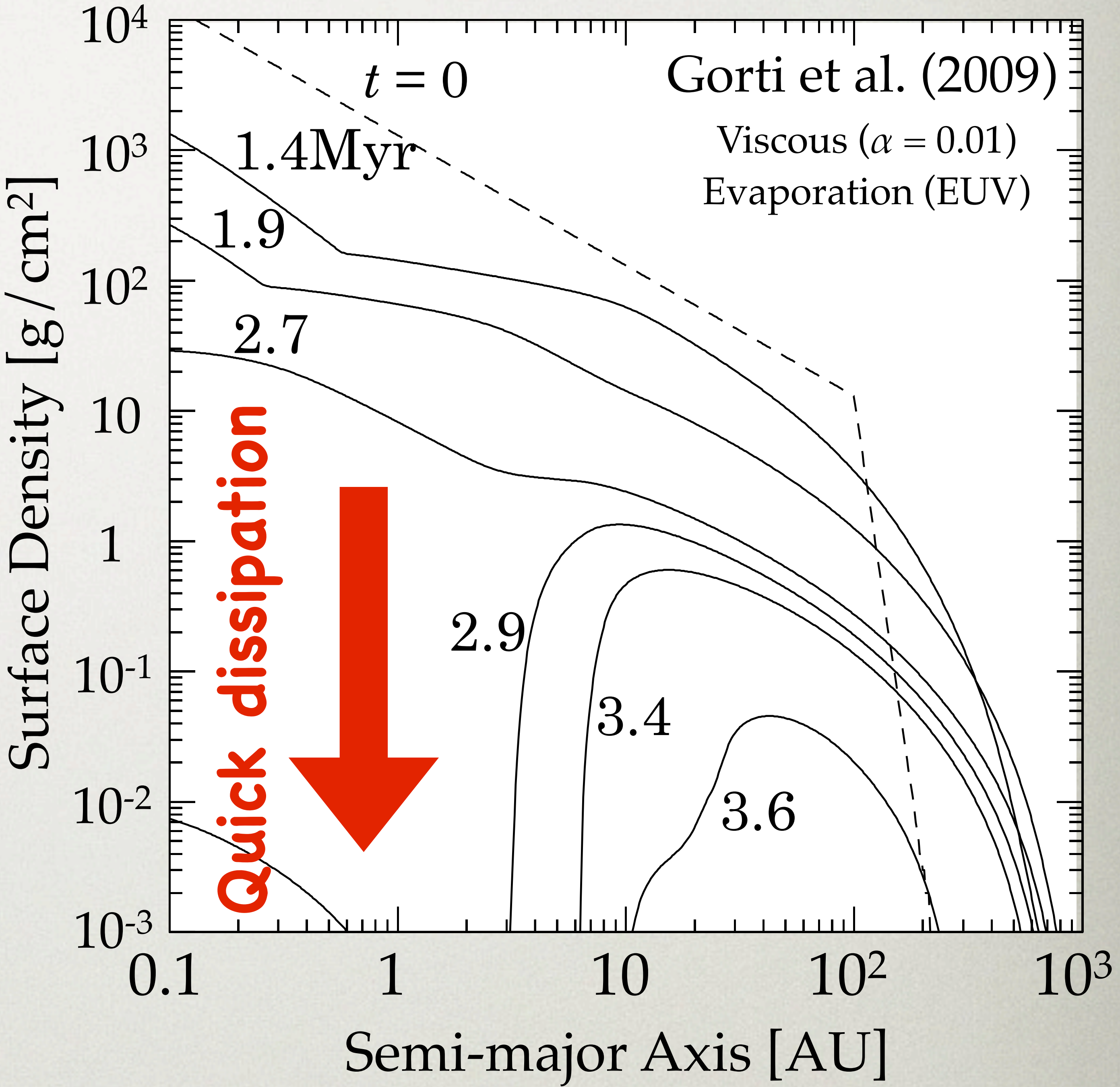


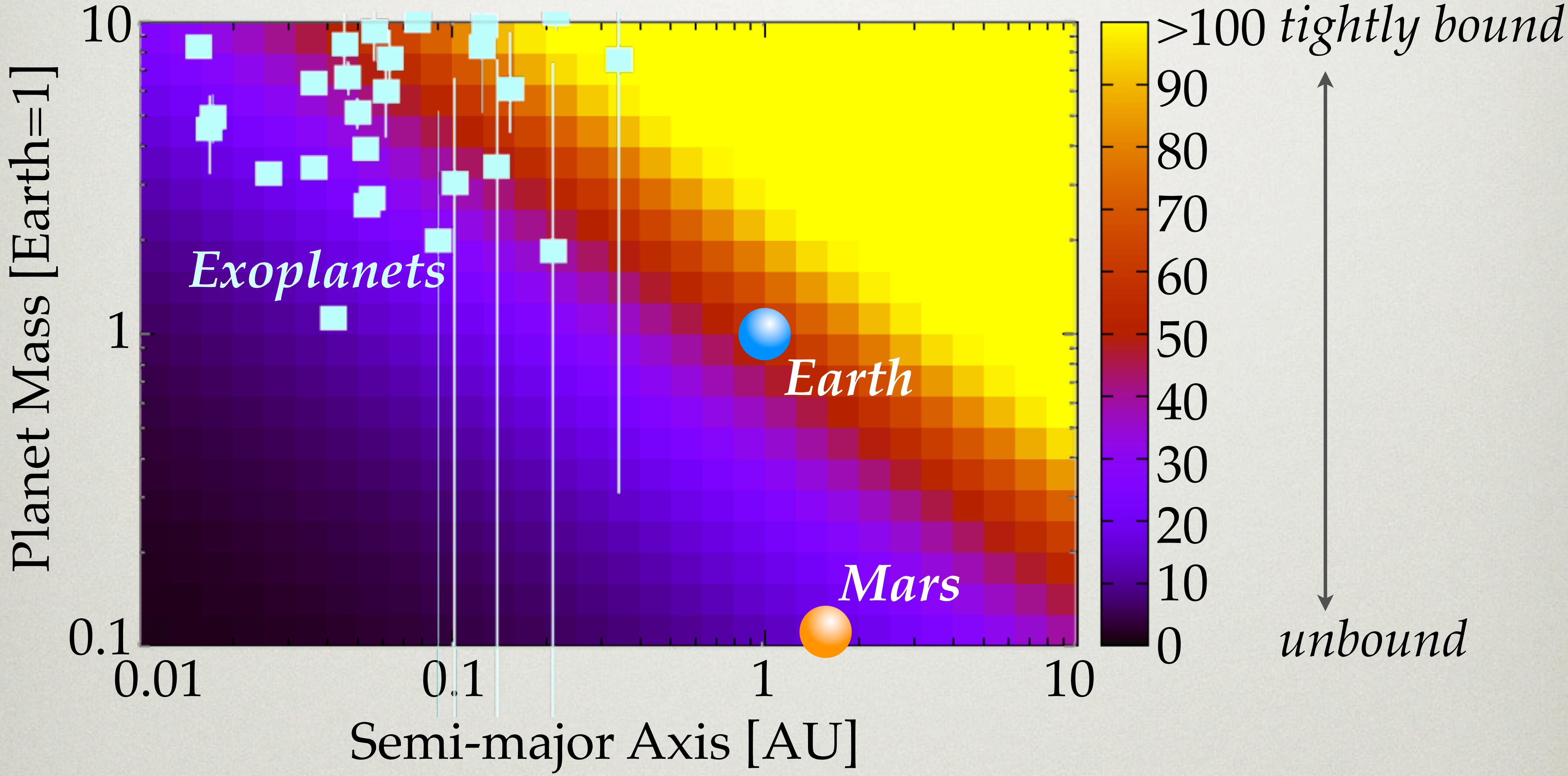
Illustration from William & Cieza (2008)



- **Disk dissipates in a few Myr**
- **Photo-evaporation results in quick dispersal of inner disk**

Disk Property & Planet Mass

“Escape” parameter $\lambda \equiv GM_p\mu/R_pkT_{\rm disk}$

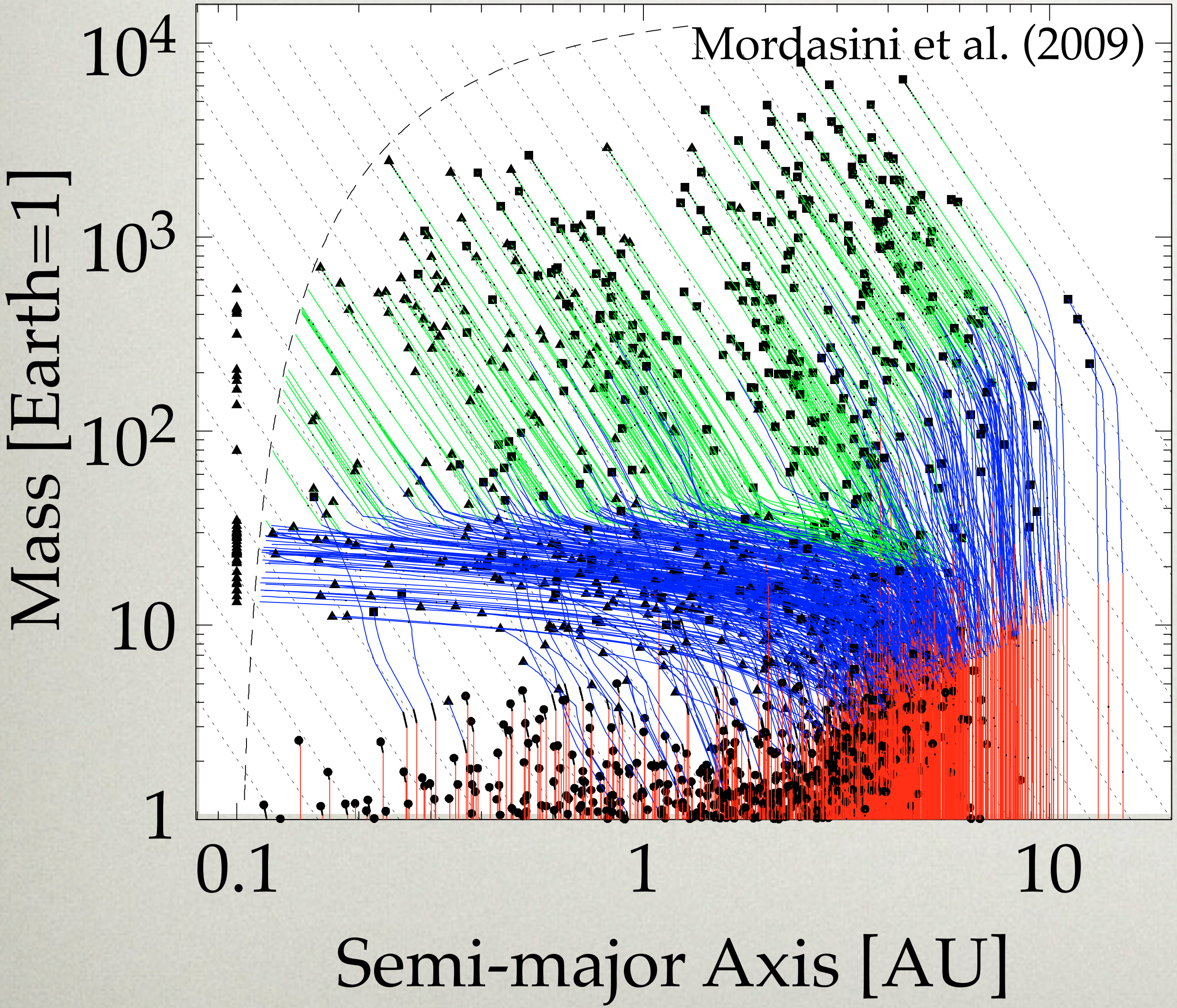


Embedded atmospheres of close-in low-mass planets are less bound and thus vulnerable to disk properties

Population Synthesis

Integrated planet formation models

Ida & Lin (2004, 2005, 2008ab, 2010)
Mordasini et al. (2009ab,2012abc), Alibert et al. (2011, 2013) etc.



Physics included

- *Disk structure & dissipation*
- *Solid accretion*
- *Gas accretion*
- *Orbital migration*

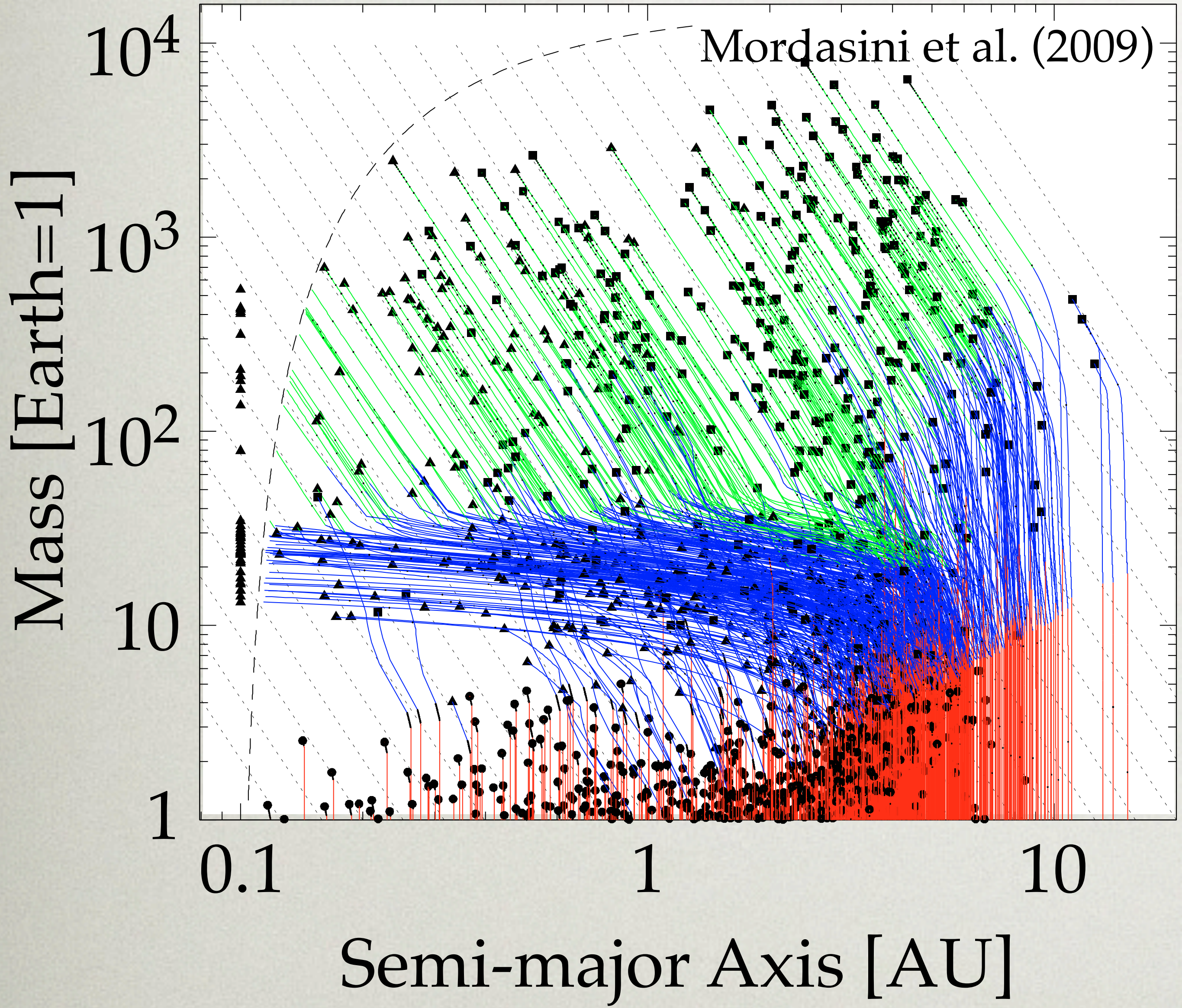
Monte Carlo variables

- *Dust/gas ratio in disk*
- *Initial disk mass*
- *Disk photoevaporation rate*
- *Initial semi-major axis of seed embryo*

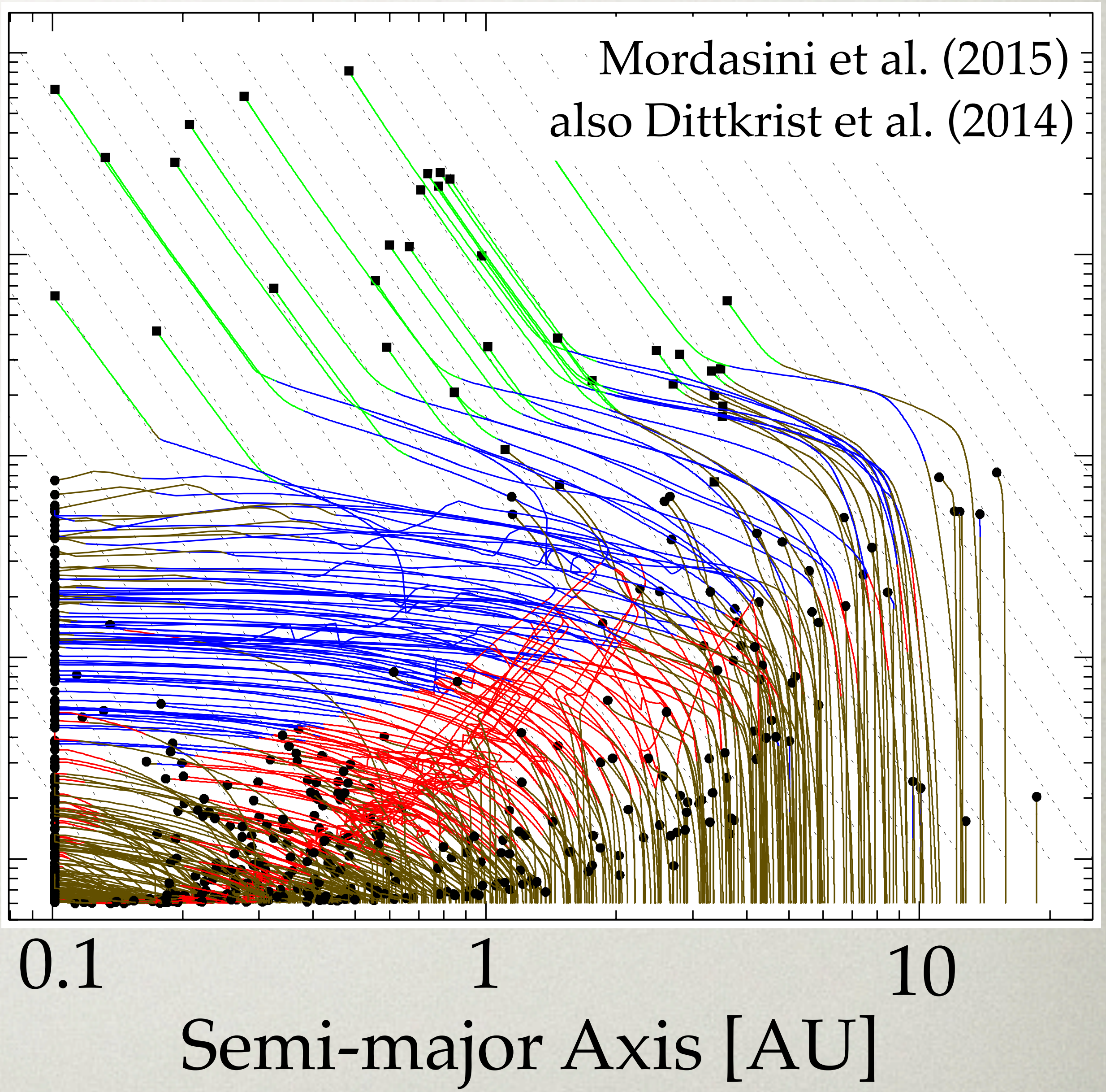
Population Synthesis

A recent progress in migration theory

isothermal, linear (reduced)

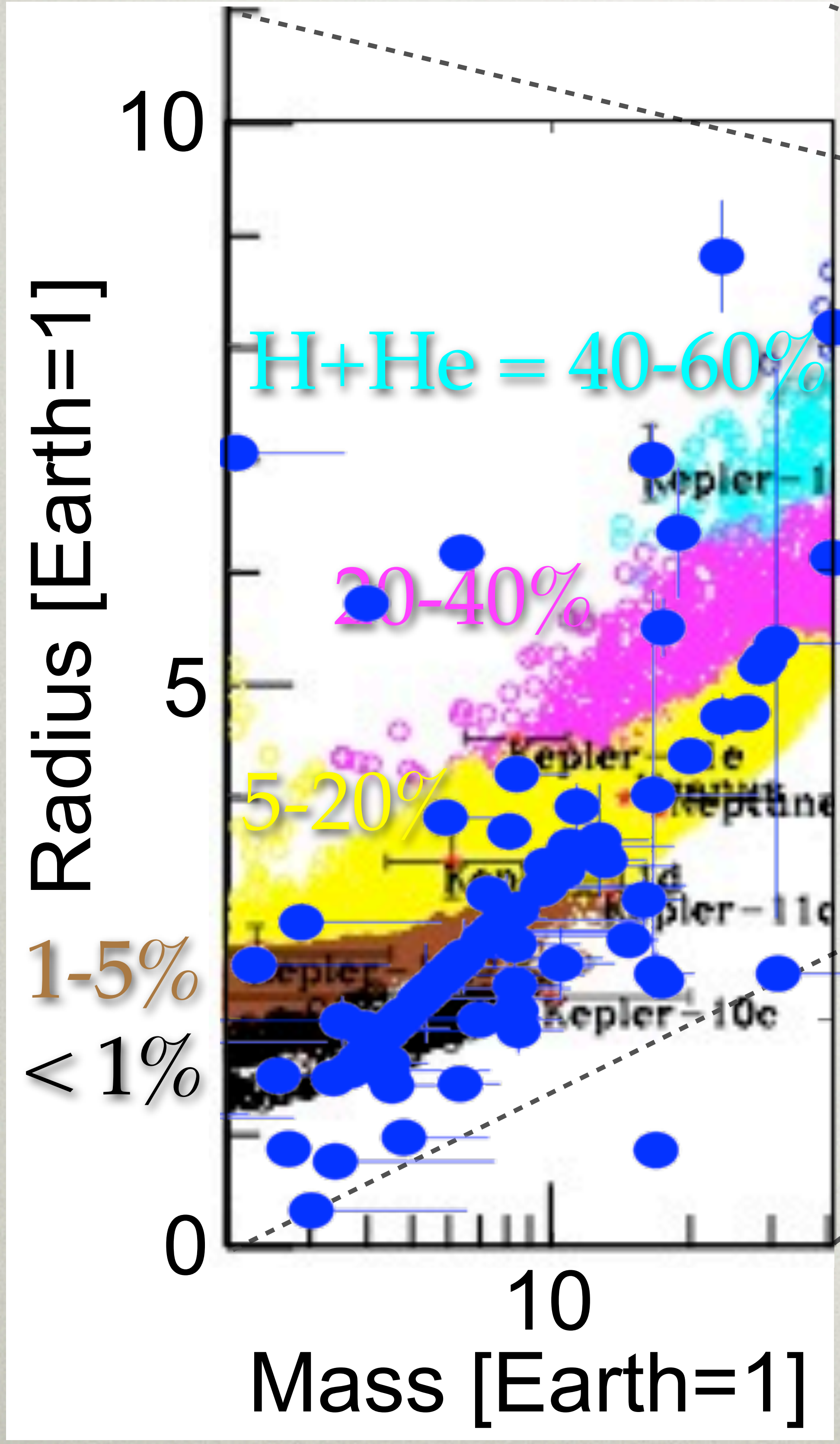

Mordasini et al. (2009)

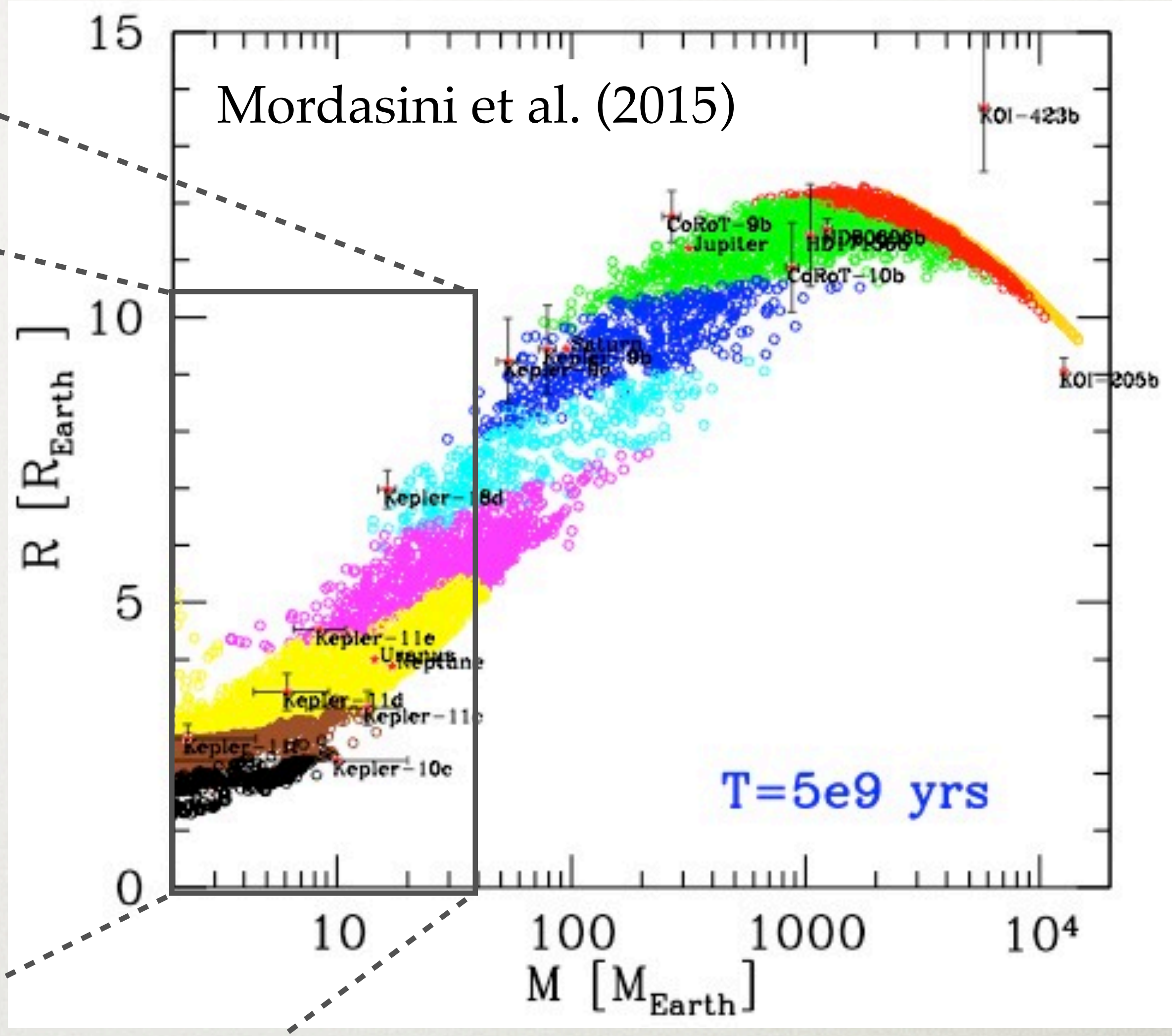
non-isothermal, non-linear


Mordasini et al. (2015)
also Dittkrist et al. (2014)

Through back-and-forth migration, rocky planetary embryos sweep planetesimals to be super-Earth-mass planets

Population Synthesis Bulk Composition




Mordasini et al. (2015)

- Masses & radii of observed planets are within the theoretically predicted range
- Observed low-mass planets seem to be denser than theoretically predicted
- **Few low-mass planets with > 10% H/He**

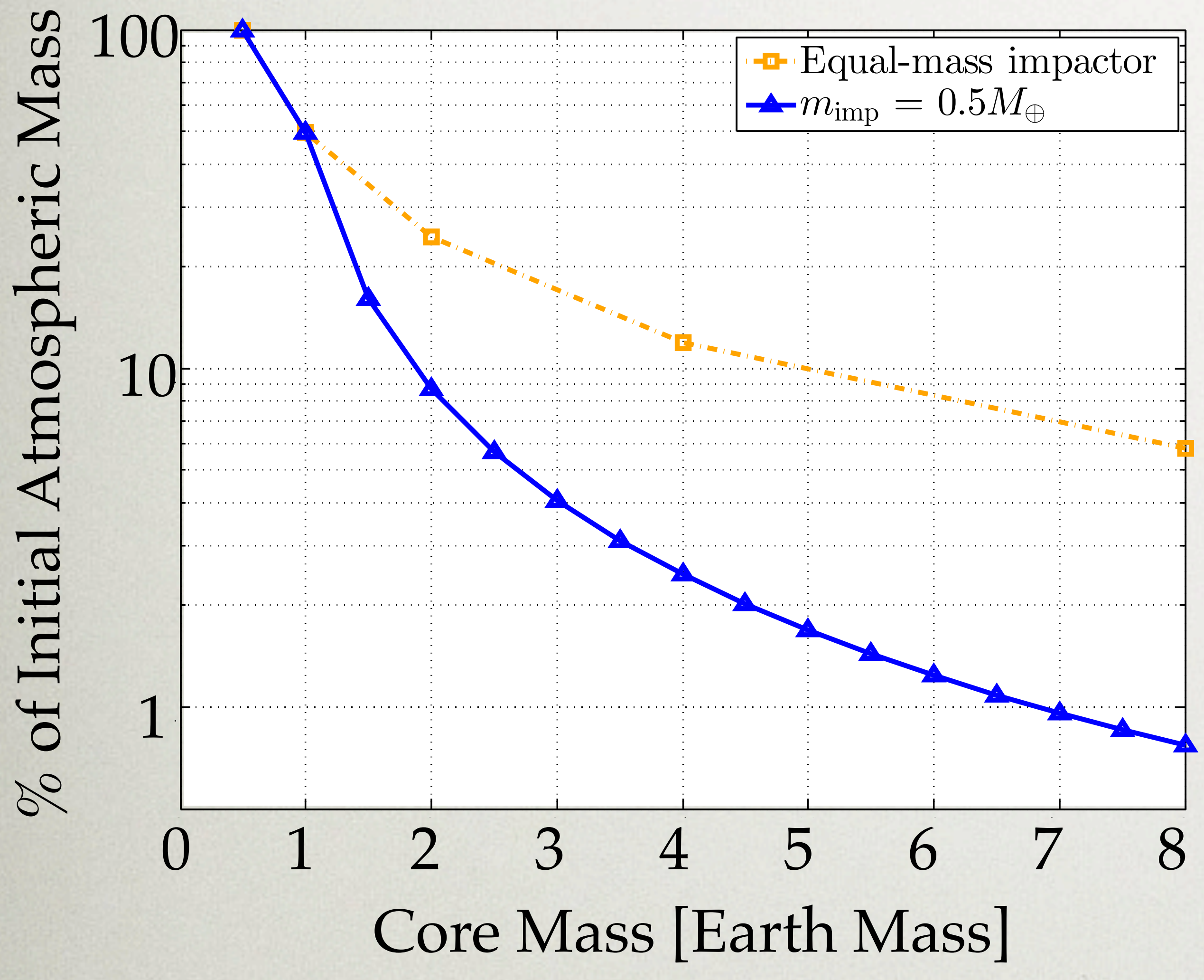
Missing Processes

- Subsequent (i.e., post-migration) modification to planetary composition
    1. Collisional erosion
    2. Post-giant-collision gas accretion
    3. Photo-evaporative mass loss

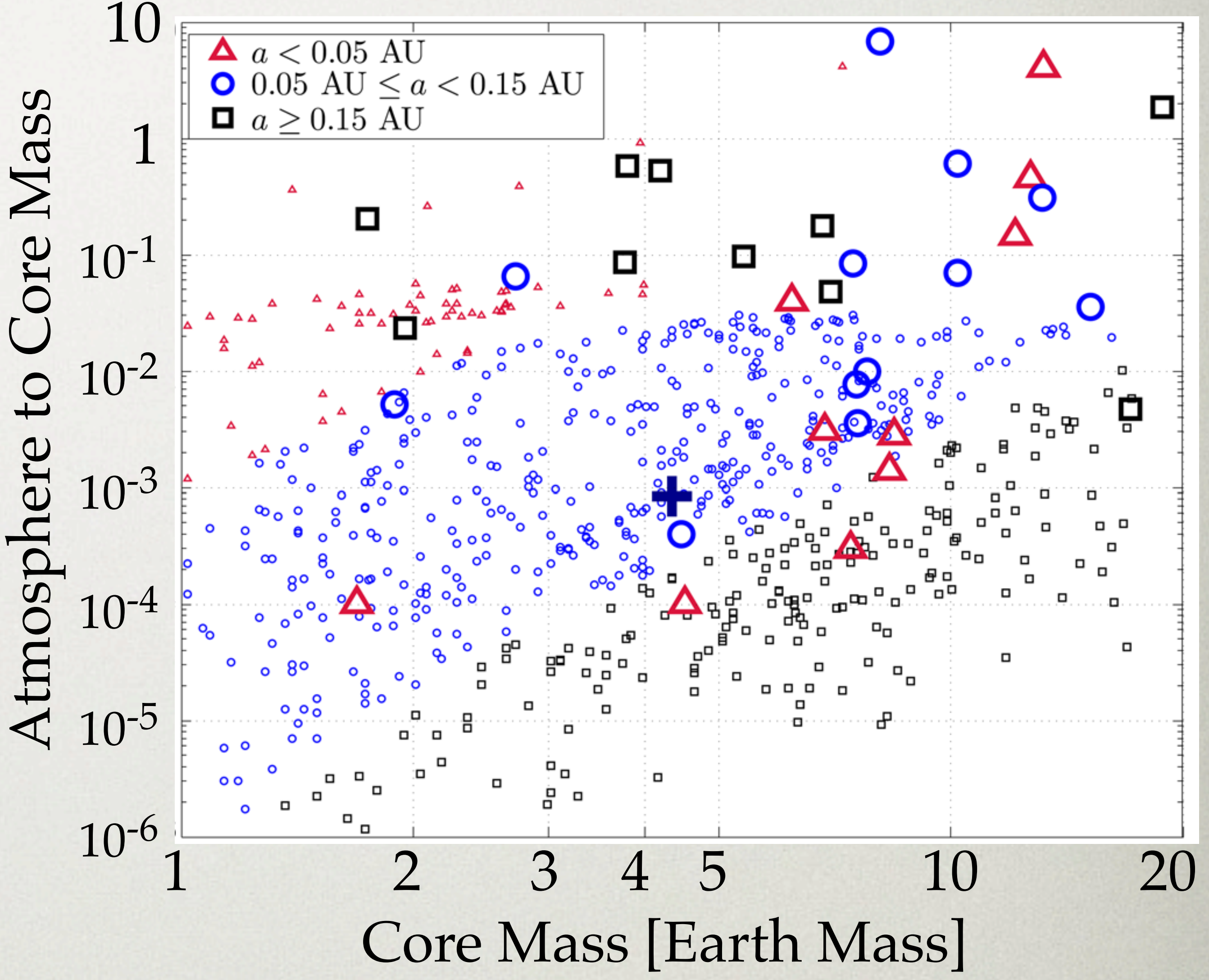
Collisional Erosion

Inamdar & Schlichting (2015)

Atmospheric Mass Lost by Collision



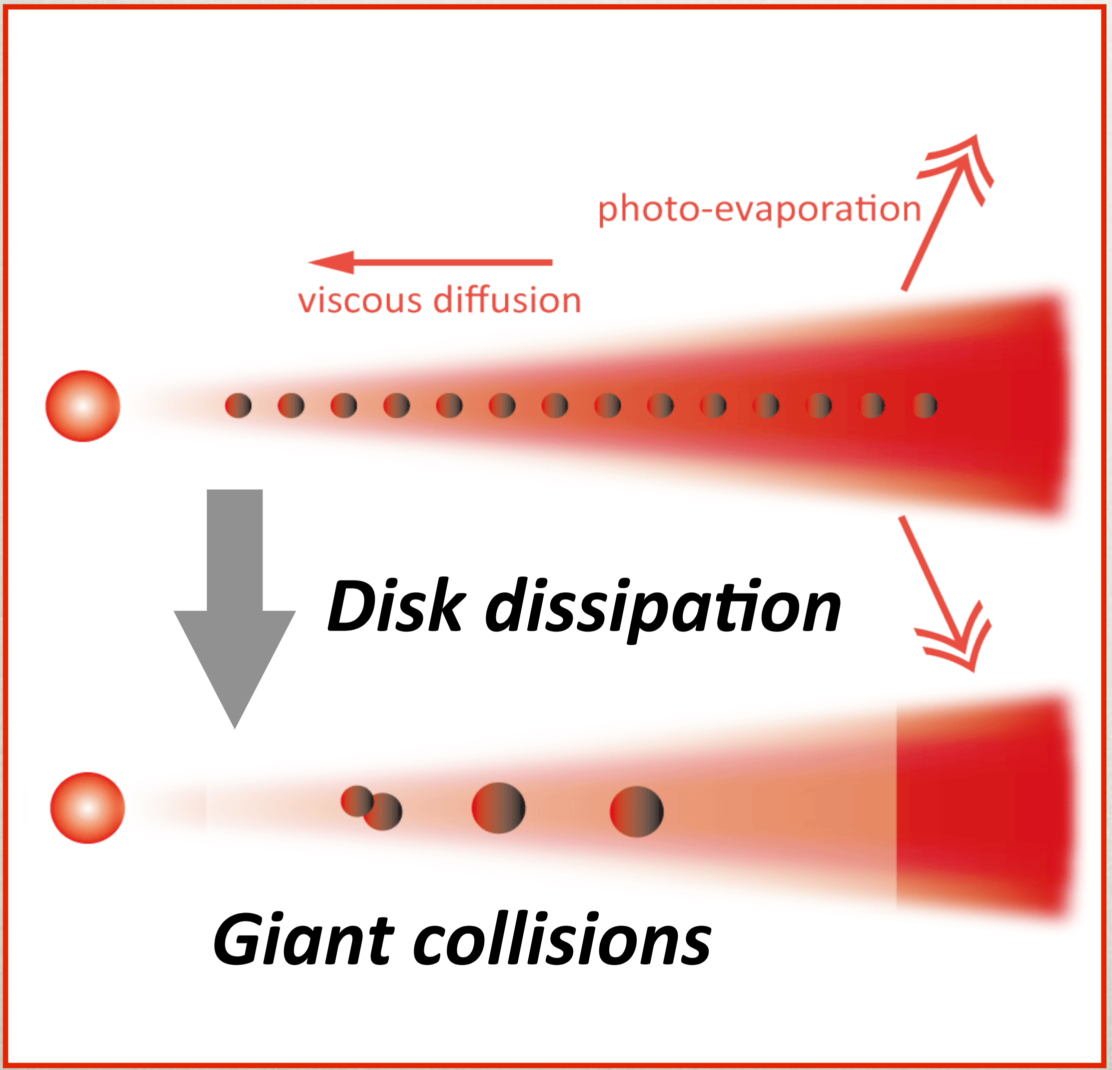
Comparison with Observation

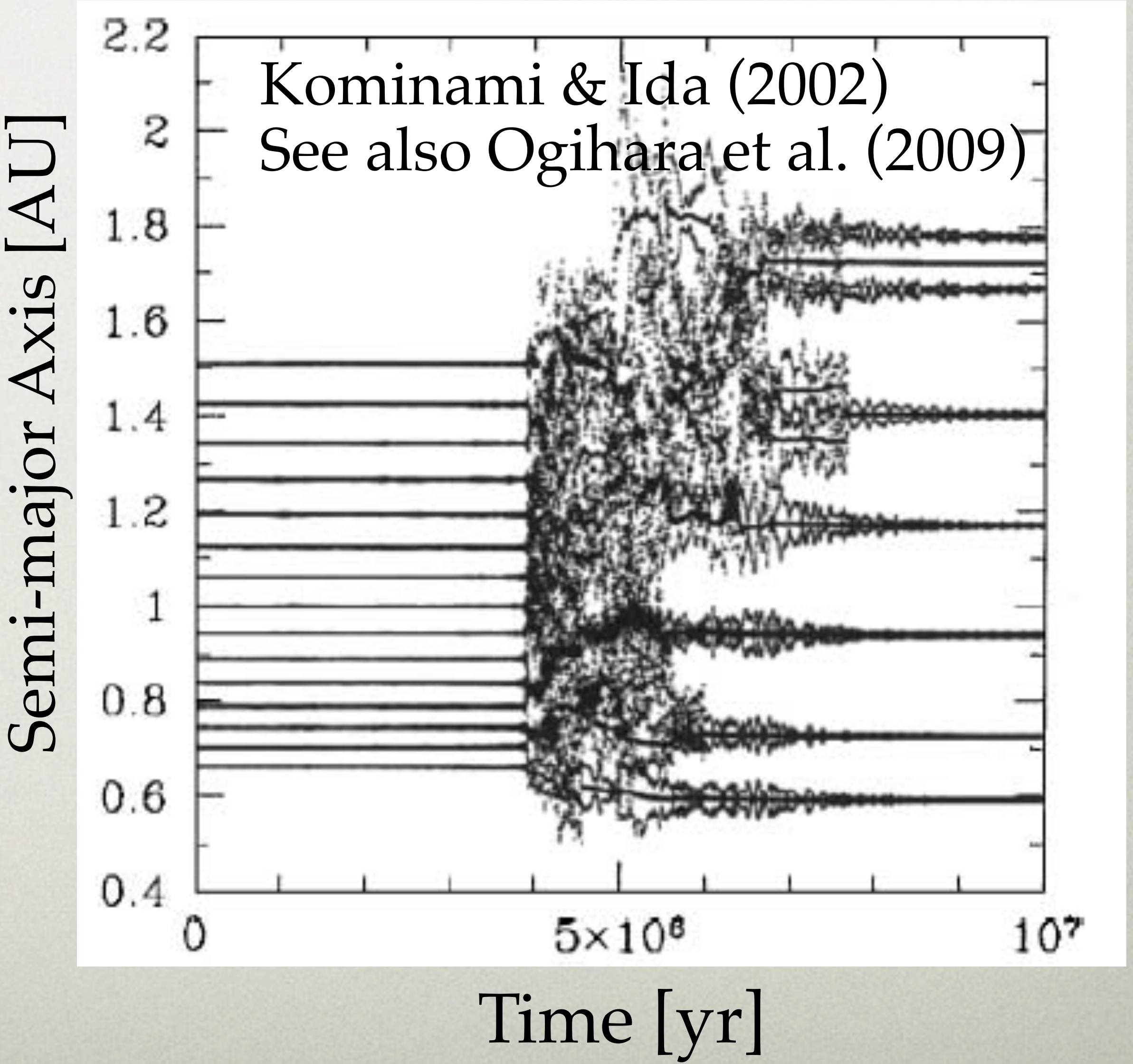


- So effective in removing H/He atmosphere significantly.
- **Giant collisions after disk dispersal are incompatible with the presence of low-density low-mass planets.**

Giant Collisions *during* Disk Dissipation

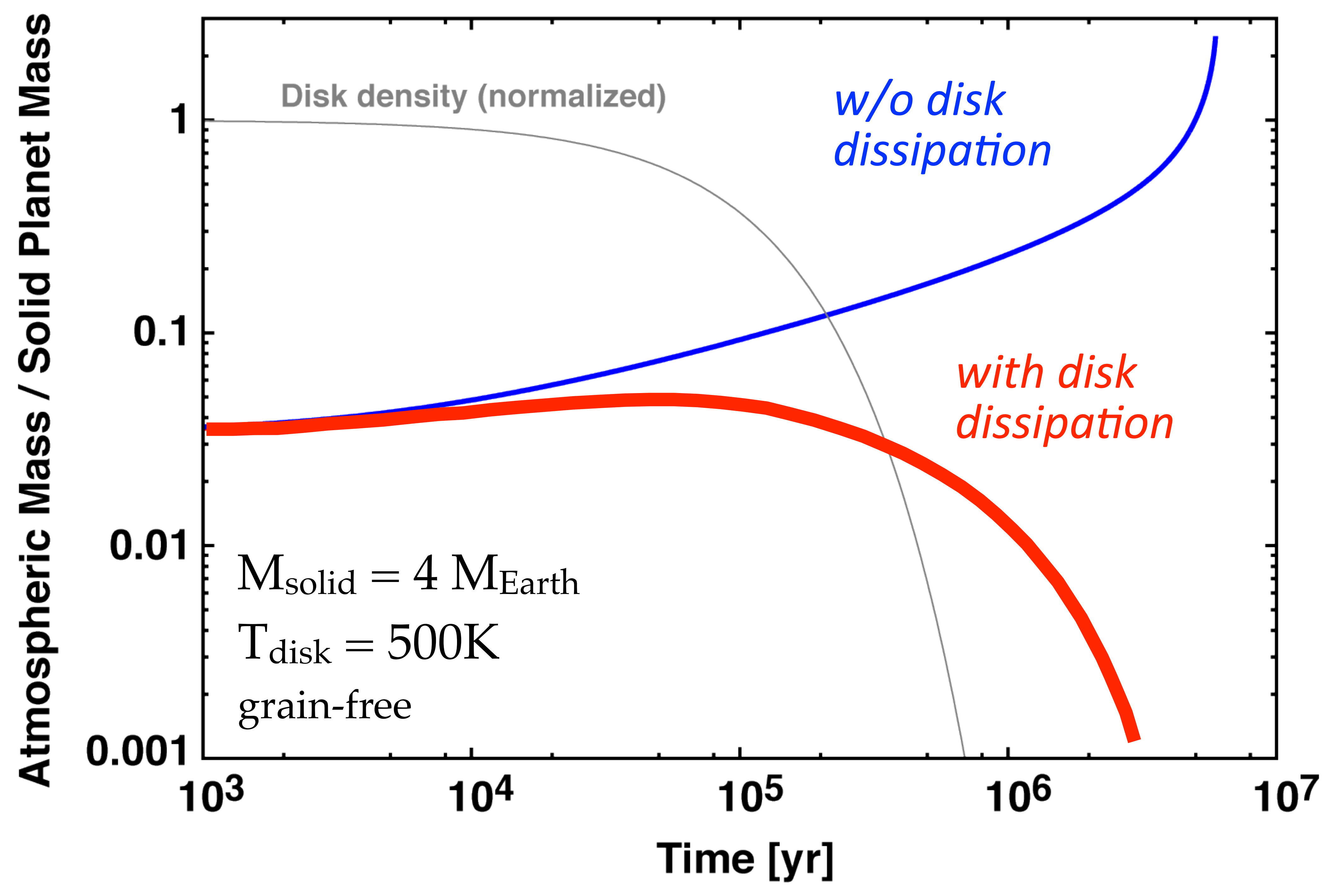
- Successive orbital migration of planetary embryos forms a compact multiple-embryo system via resonance trapping.
- Disk begins to dissipate, triggering orbital instability of the multiple-embryo system and then giant collisions
- The merged planet captures gas from the dissipating disk.





Kominami & Ida (2002)
See also Ogihara et al. (2009)

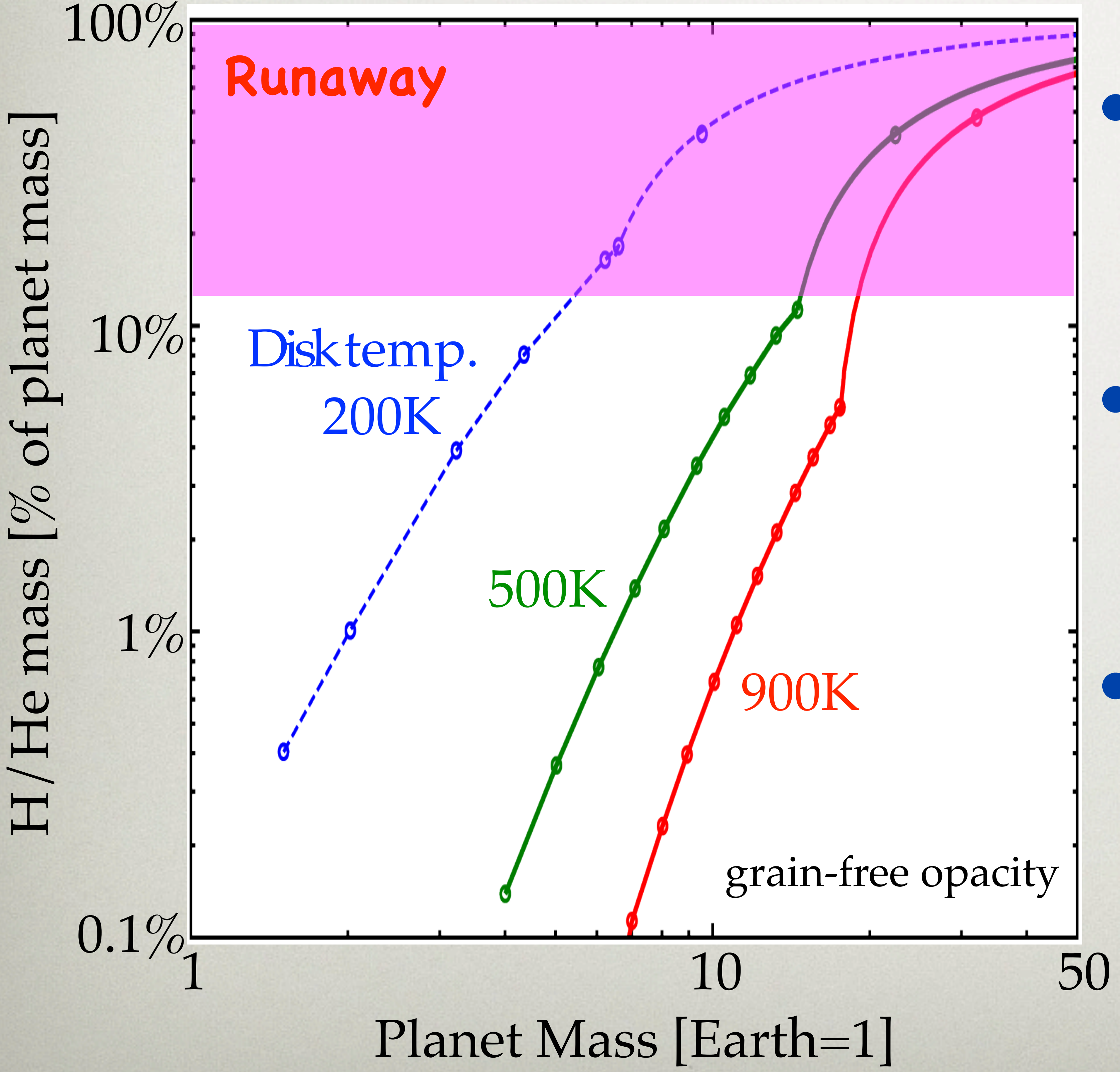
Post-Giant-Collision Gas Accretion



Ikoma & Hori (2012)

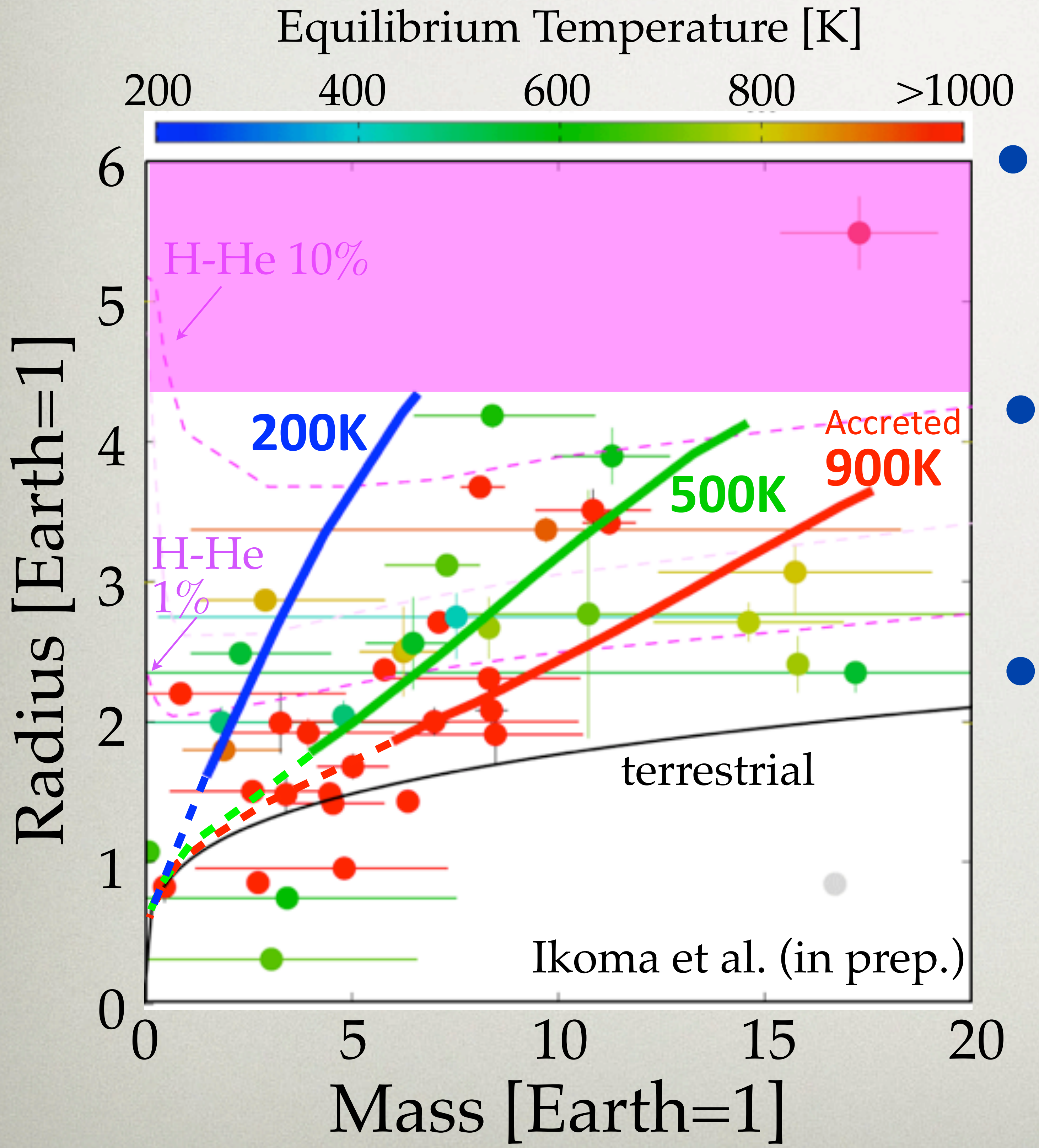
Post-Giant-Collision Gas Accretion

Final Mass of Accreted Atmosphere Ikoma & Hori (2012)



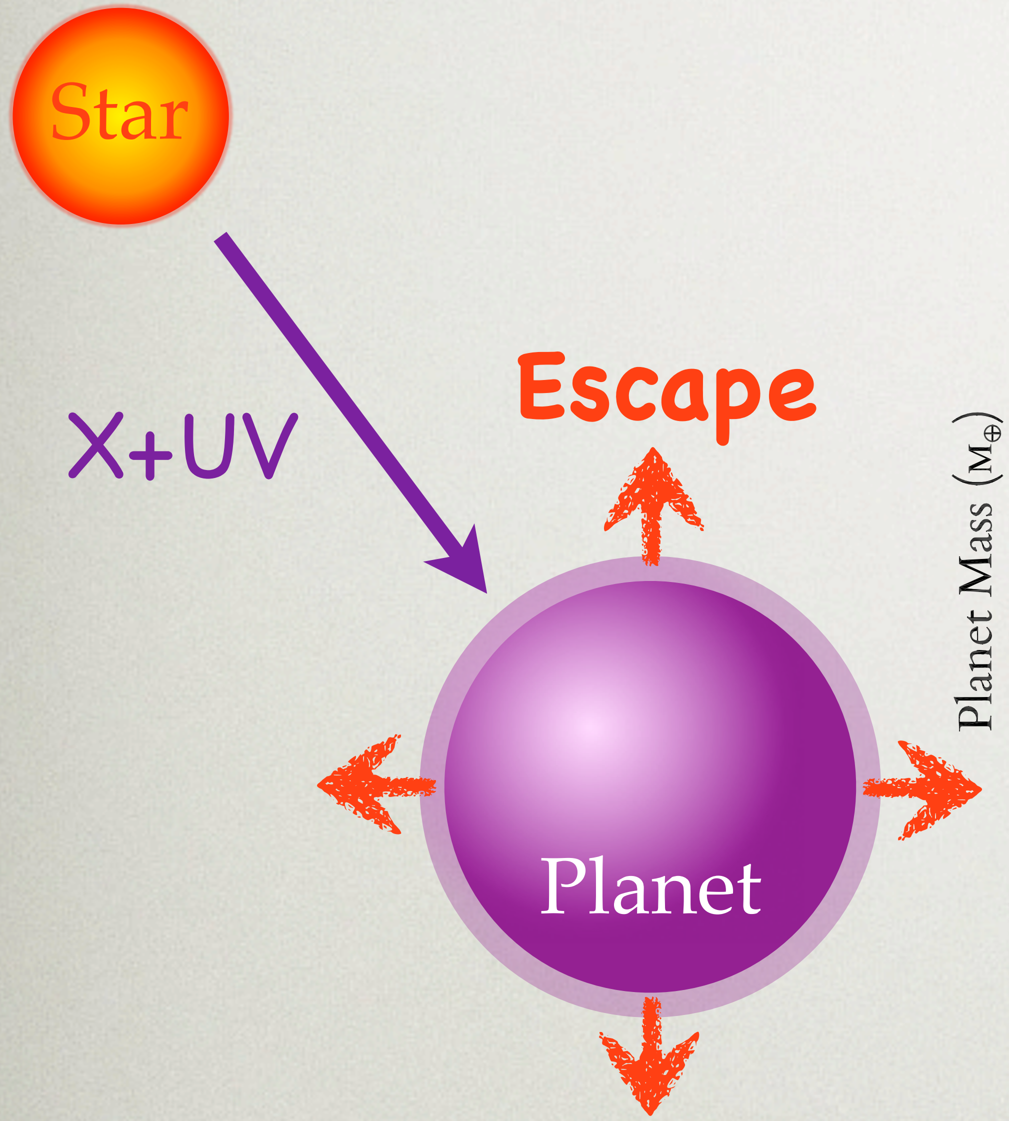
- After giant collision, cores can capture significant amounts of H/He even in dissipating disks
- About 10% is the threshold beyond which runaway gas accretion occurs
- Dependent strongly on planet mass and disk temperature

Post-Giant-Collision Gas Accretion



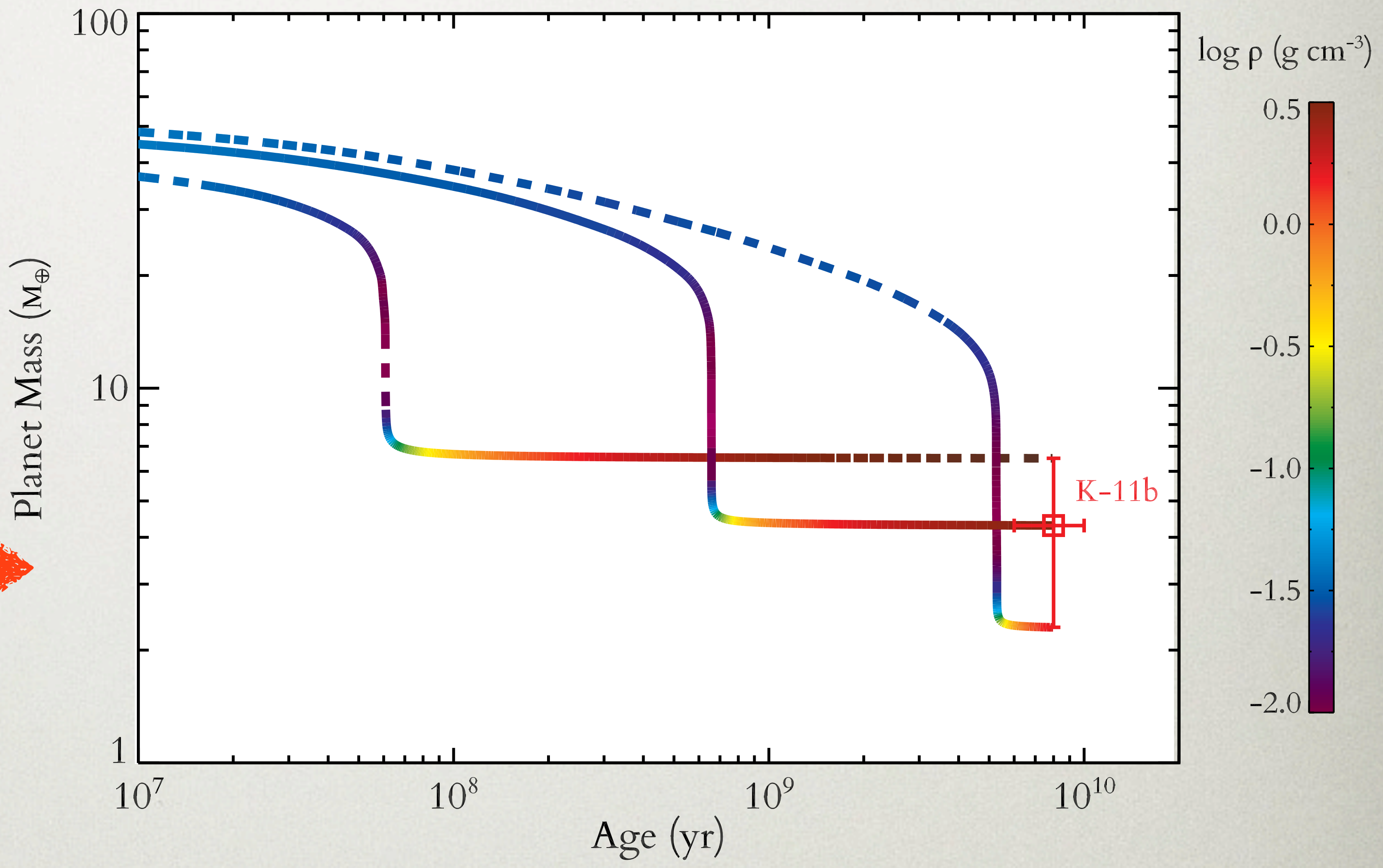
- Few planets have been detected in the runaway domain.
- Most of the planets are near or below the theoretical lines for hot/warm environments.
- However, radii of some planets are larger than theoretically predicted.
  - The body is not rock but ice/water ?
  - The disk was colder than assumed ?

Photo-evaporative Erosion



Mass Evolution of Kepler-11b

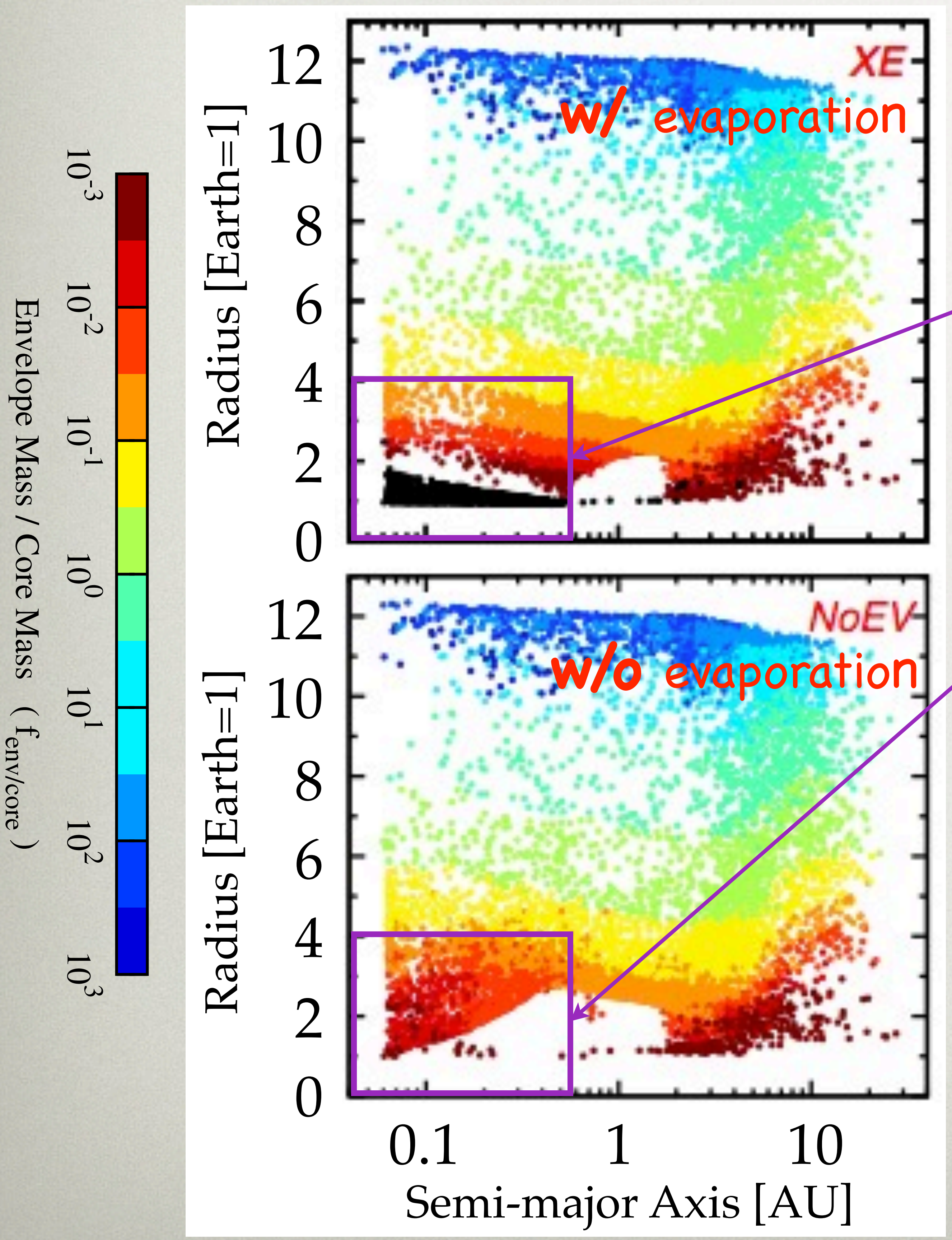
Lopez et al. (2012)



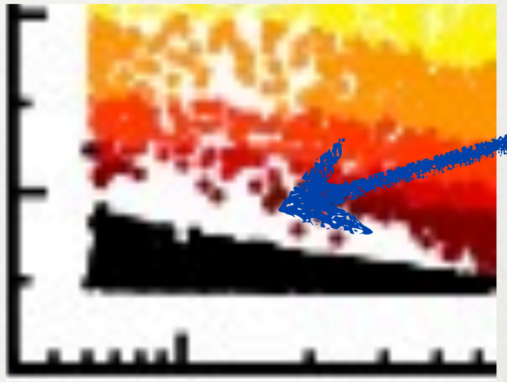
Coupled thermal evolution and photo-evaporative mass loss

Close-in low-mass planets have lost significant amounts of H/He for billion years.

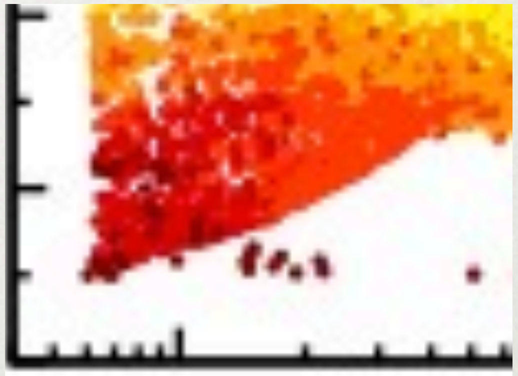
Photo-evaporative Erosion



Population Synthesis by Jin et al. (2014)



Evaporation valley



See also
Lopez et al. (2012)
Owen & Wu (2013)
Lopez & Fortney (2013)

- **H/He atmospheres of < ~10% are removed readily, which results in an evaporation valley.**
- **Such clear deficit is NOT observed in the distribution of KOIs.**

Contribution of Icy Planets

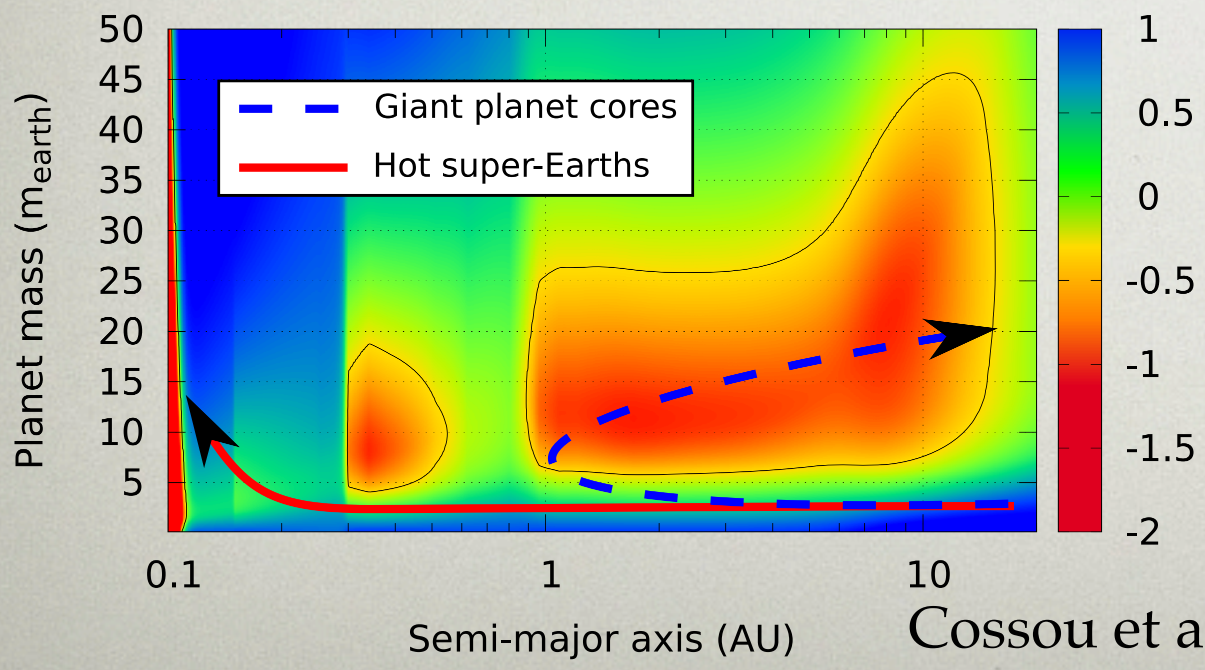
- Contribution of planets accreted in cool environments may be needed.

  Bodenheimer & Lissauer (2014)

- Gravitational interaction among protoplanets are important.

  Alibert et al. (2013)

- Might conflict with the presence of many cool gas giants



Cossou et al. (2014)

Effect of Gravitational Interaction

Alibert et al. (2013)

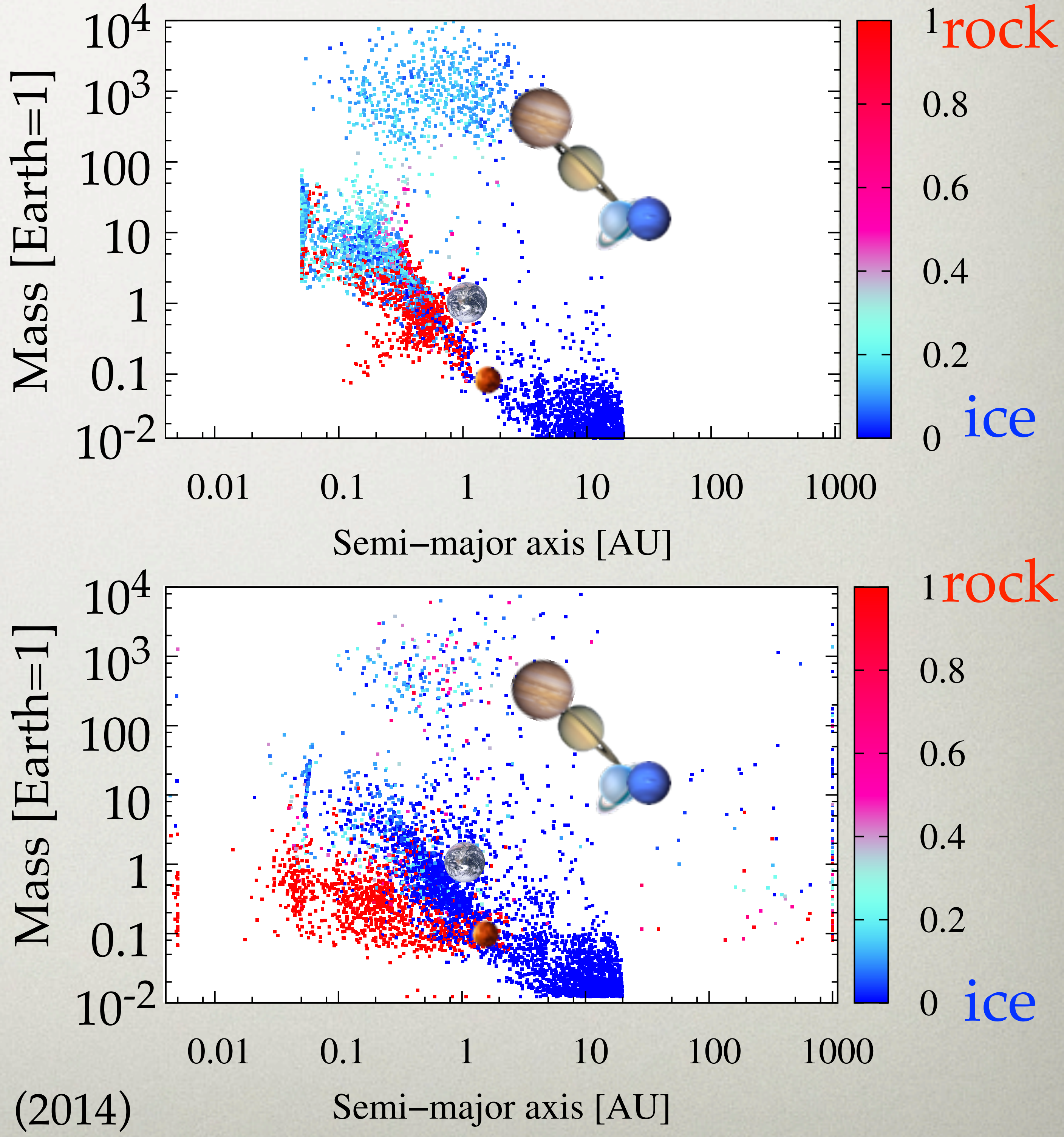
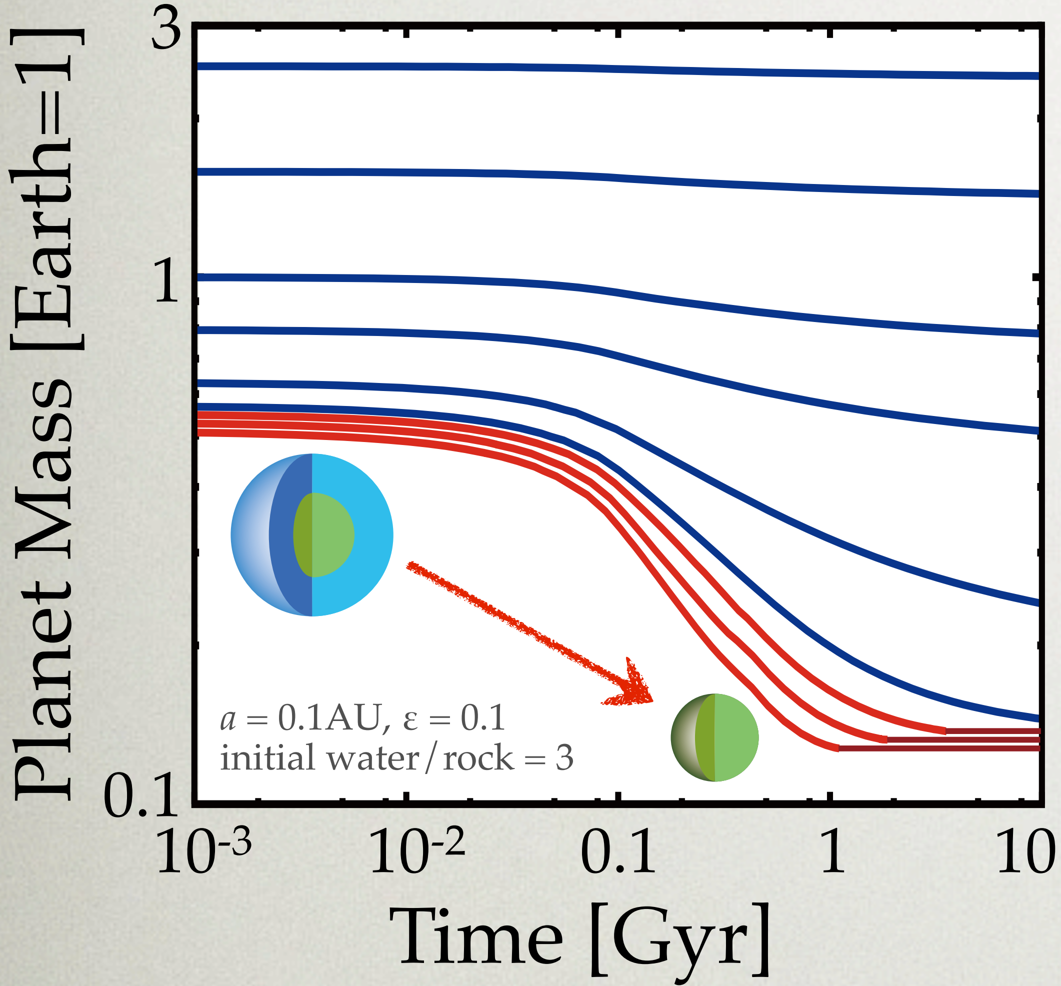
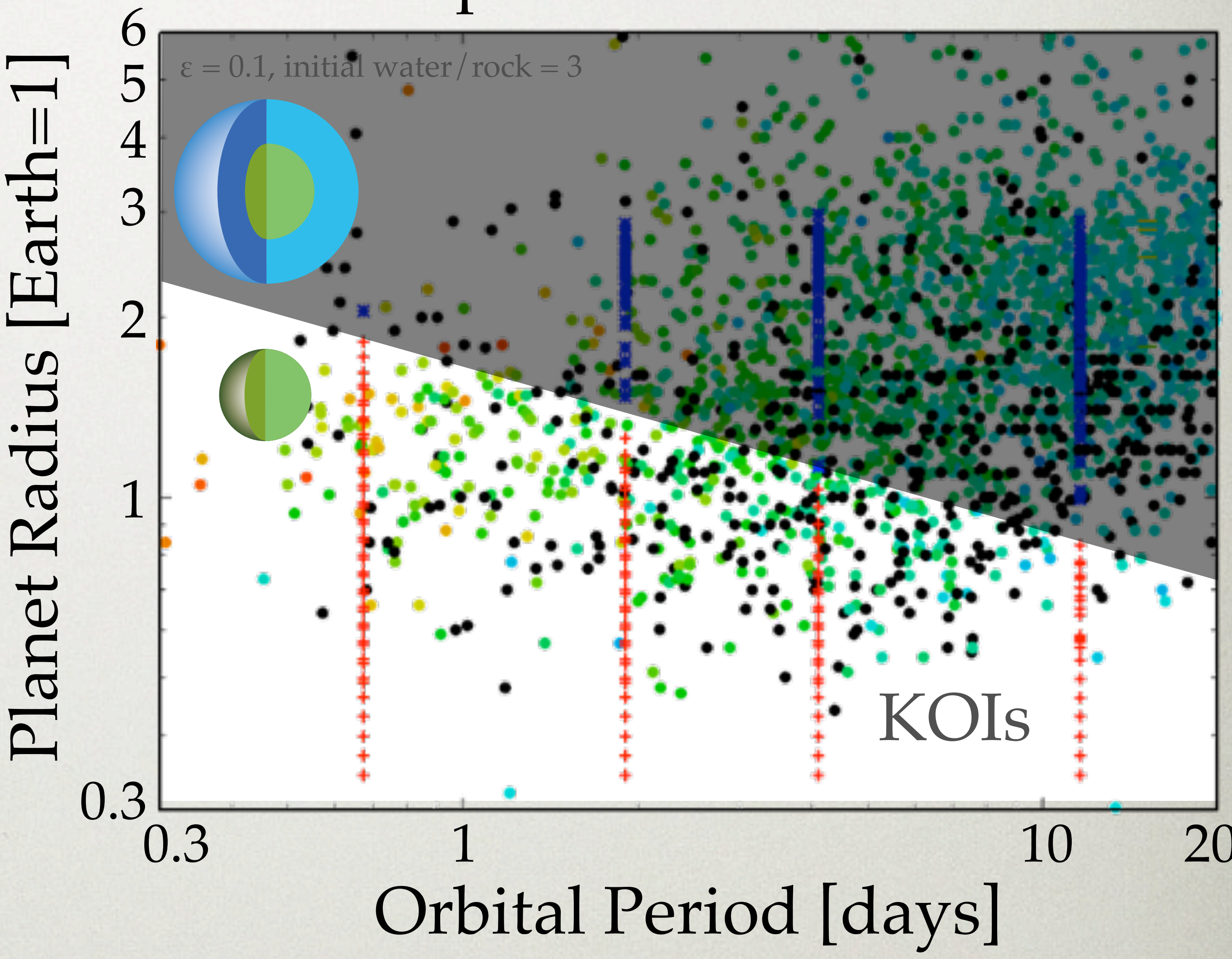


Photo-evaporation of Water-Worlds

Simulation Result of UV-Driven
Photo-evaporative Mass Loss



Fate of Water-Worlds
Comparison with KOIs

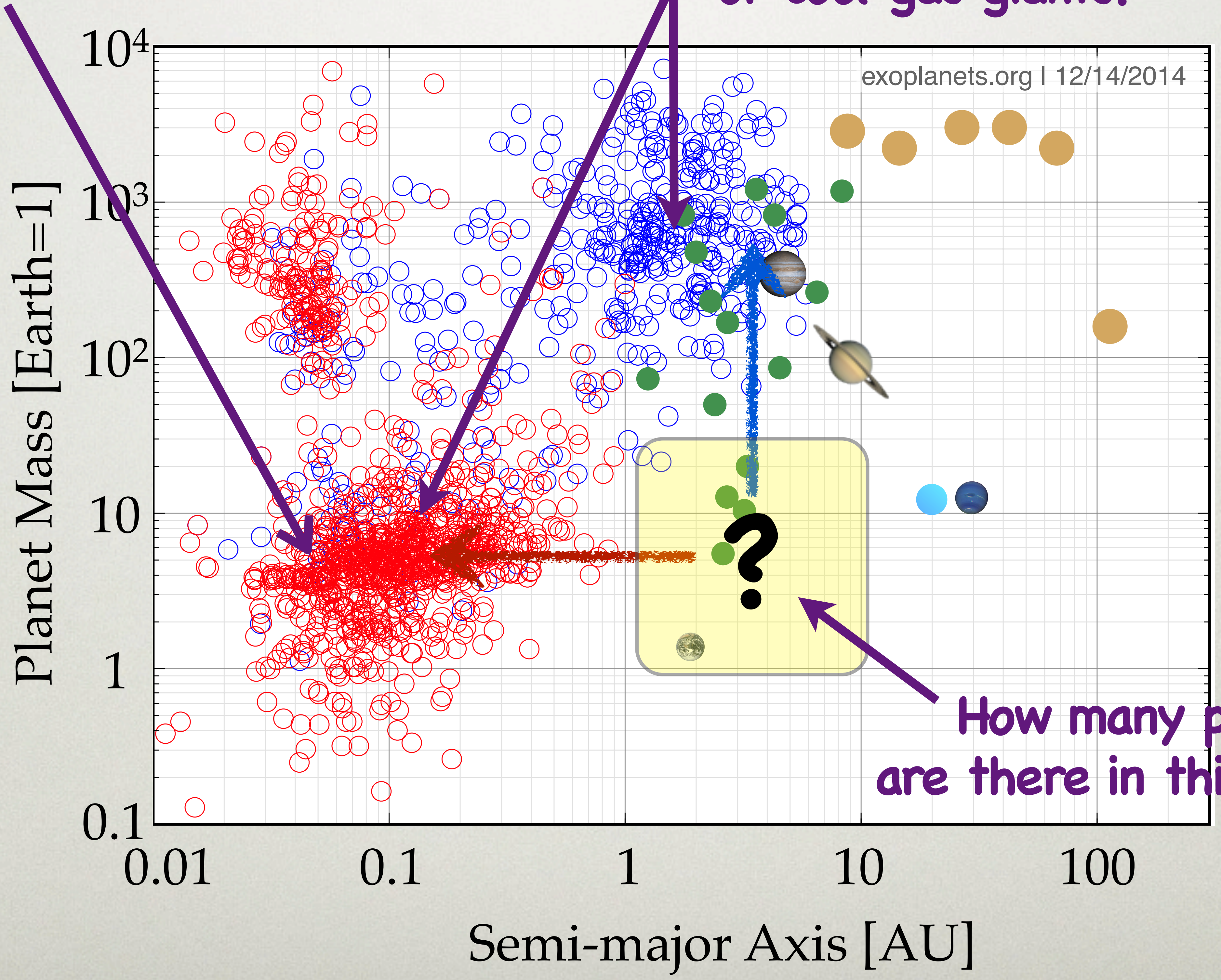


- A similar evaporation valley may be detected
- There must be remnants of evaporated icy planets or evaporating icy planets.

Kurosaki, Ikoma, & Hori (2014, A&A)

Are icy components detected in the atmosphere?

Which is dominant, close-in low-mass planets or cool gas giants?



How many planets are there in this domain?

Summary & Conclusions

- Close-in low-mass exoplanets (super-Earths and mini-Neptunes) are quite diverse in bulk density.
- From viewpoints of planet formation theory, the diversity cannot be explained only by rock and H/He. Contribution of ice would be needed.
- The effects of orbital migration and gravitational interaction among planetary embryos and also the condition for gas giant formation (see P31 Venturini) must be investigated in more detail.
- Important observational constraints to be obtained:
  - The number of planets in regions of intermediate period and intermediate mass
  - The ratio of short-period low-mass planets to intermediate-period gas giants
  - Compositions of the atmospheres of close-in low-mass planets (see P19 Kawashima)