Combined models of planet formation and evolution:

The planetary mass-radius relationship

Christoph Mordasini

Max-Planck Institute for Astronomy
Heidelberg

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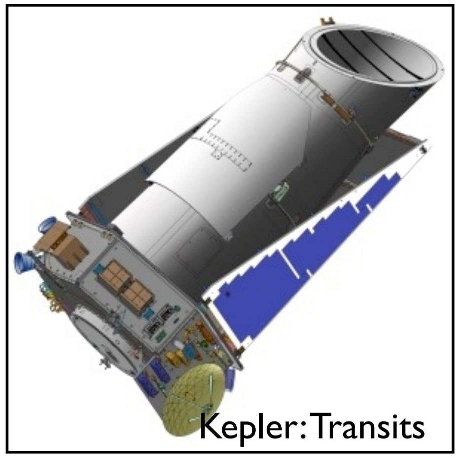
UNIVERSITÄT BERN

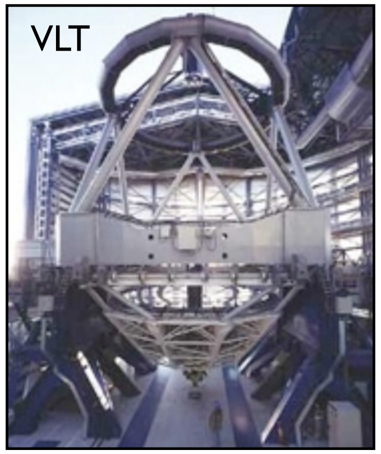
K. M. Dittkrist, P. Molliere, S. Jin, H. Klahr, T. Henning

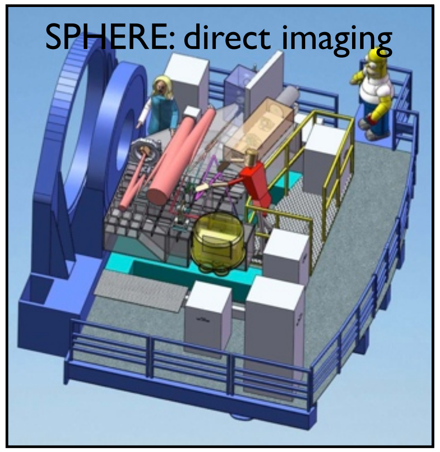
Y. Alibert, A. Fortier, W. Benz

Linking observations and planet formation

- Large number of observations from space mission (transits, spectra) and ground (radial velocity, transits, spectra, direct imaging). More to come (SPHERE, Gaia, ESPRESSO, CHEOPS, EChO..)







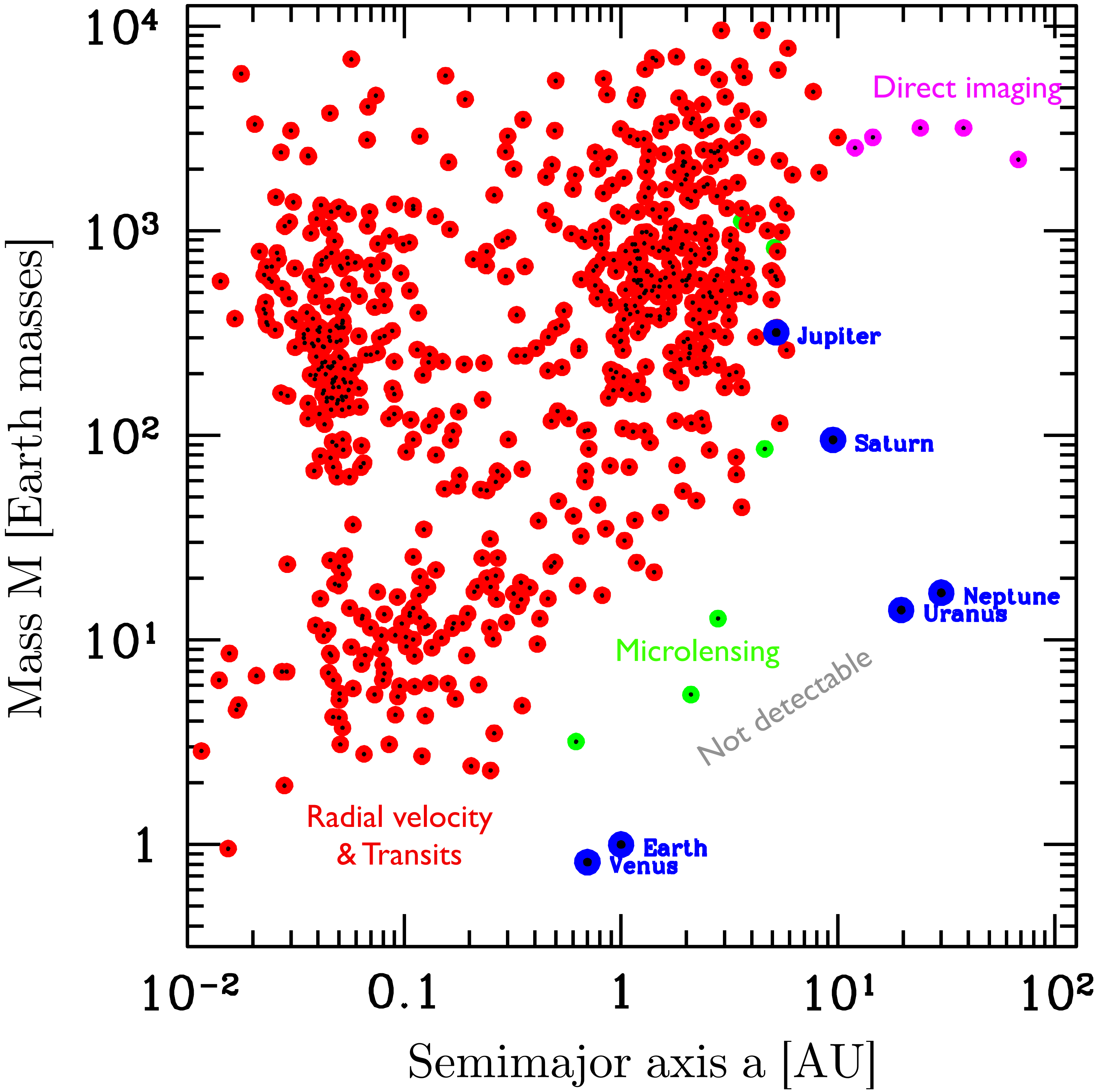
- Improve understanding of planet formation by comparing theory and observation.

- For a sufficiently large number of exoplanets: treat as a statistical ensemble.

- Planetary population synthesis: statistical comparison

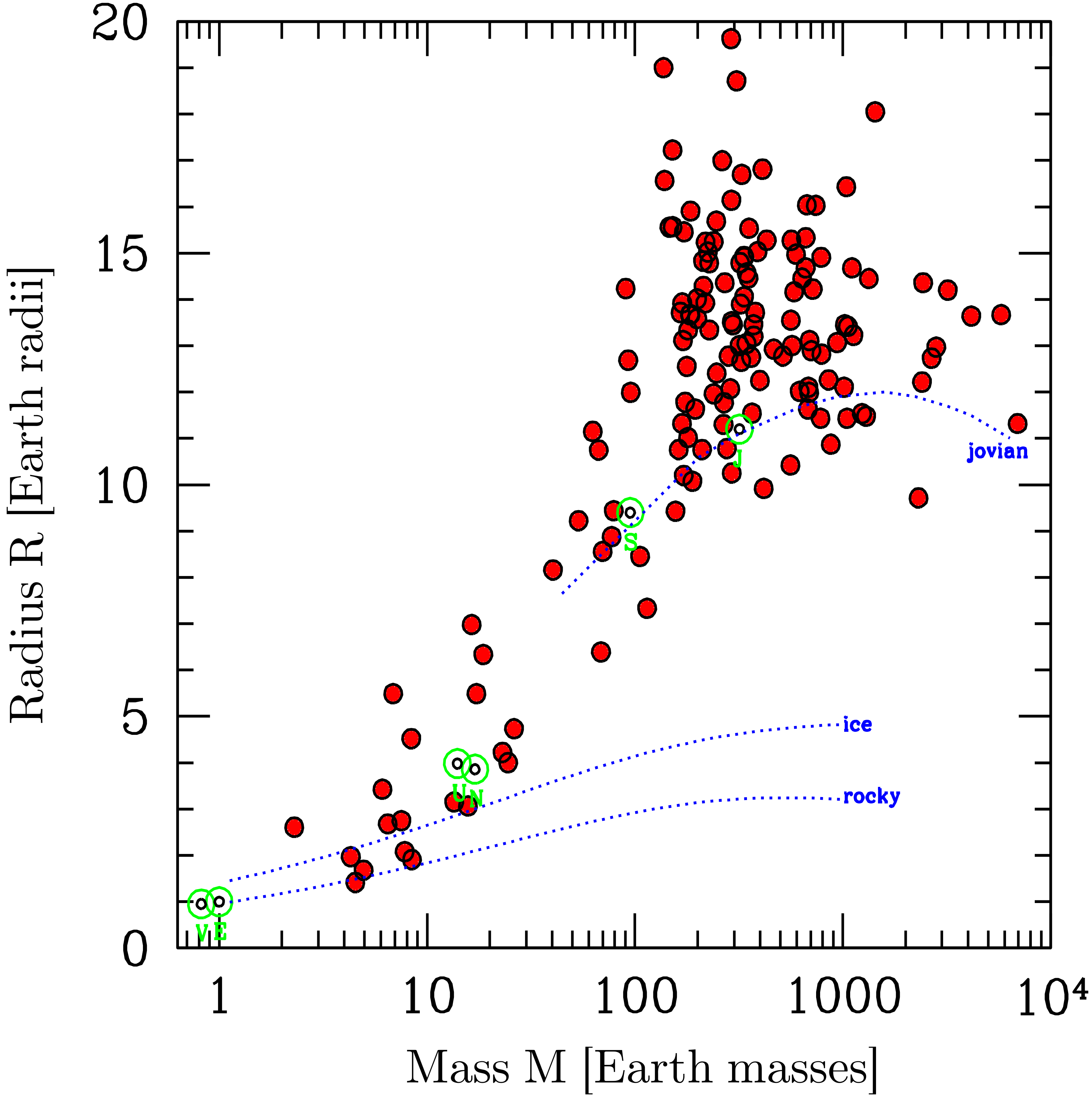
- Difficulties: 1) different techniques constrain different aspects of the theory.
  2) between formation and observation: Myrs-Gyrs of evolution.

From the a-M….



- Many fundamental constraints from the a-M diagram.

From the a-M to the M-R diagram



- M-R diagram: diversity, too!
- Bulk composition
- Constraints for formation beyond the a-M:
  - -migration (icy planets close-in?)
  - -efficiency of H/He accretion & loss
  - -runaway when? opacity?
- Understandable with theoretical models?

Adding planet evolution

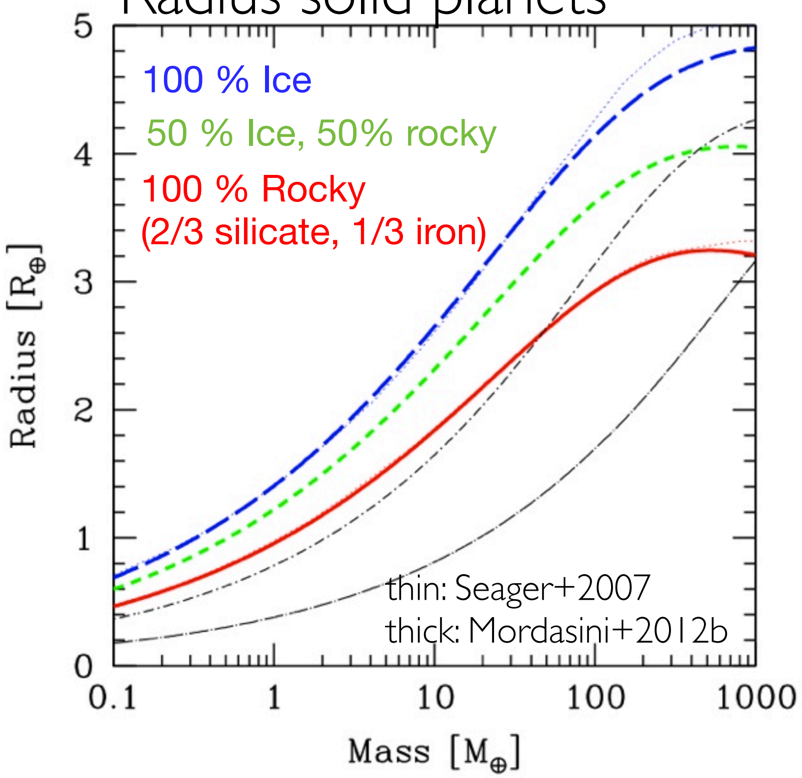
Formation: Based on core accretion paradigm, growth of seed embryo accreting gas and planetesimals in an evolving protoplanetary disk, undergoing orbital migration.

Evolution (after disk is gone): couple self consistently

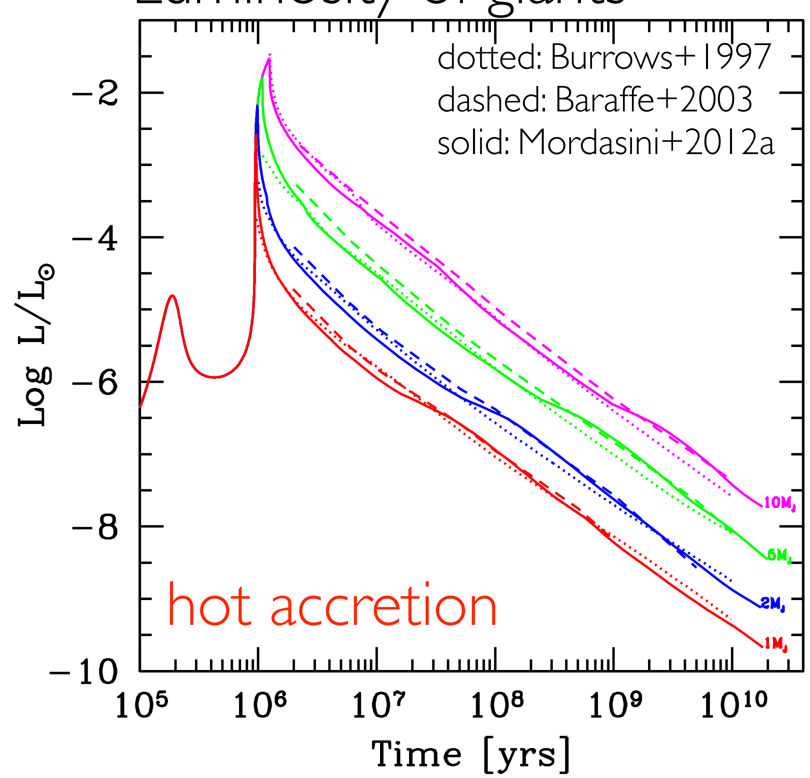
✦Solve 1D (radial) structure equations for the thermal evolution of the H/He envelope on Gyrs (cooling & contraction), including effects of stellar irradiation and radiogenic hating. Gray atmosphere.

✦Solve 1D internal structure equations for the solid core, assuming a differentiated interior.

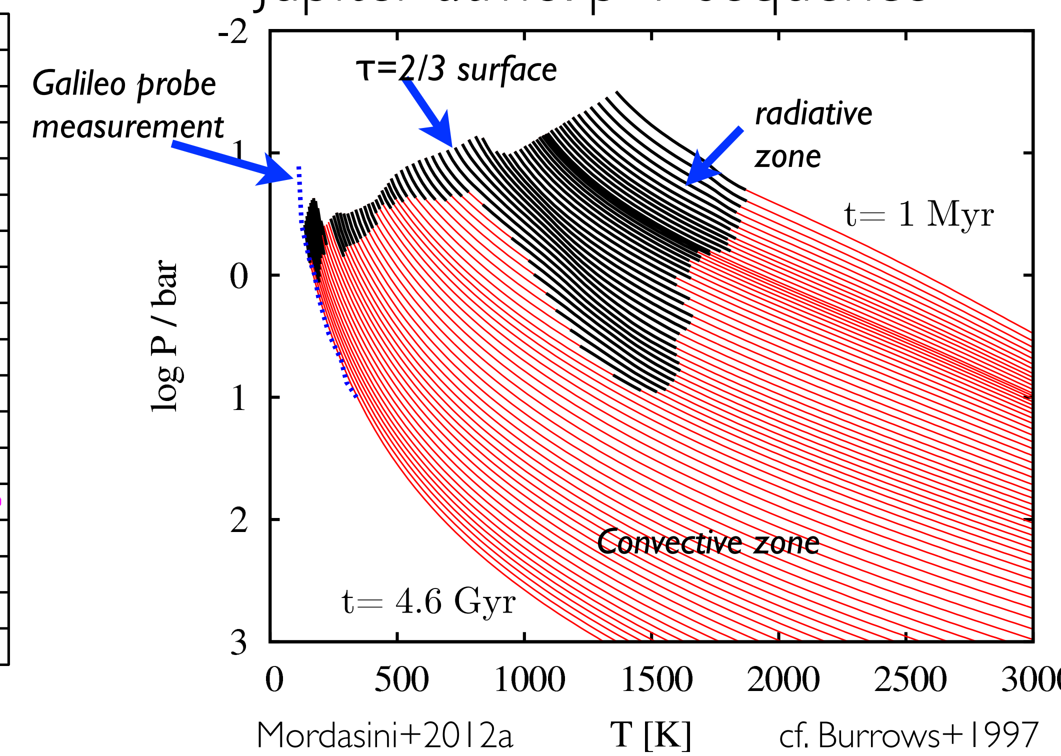
Radius solid planets



Luminosity of giants

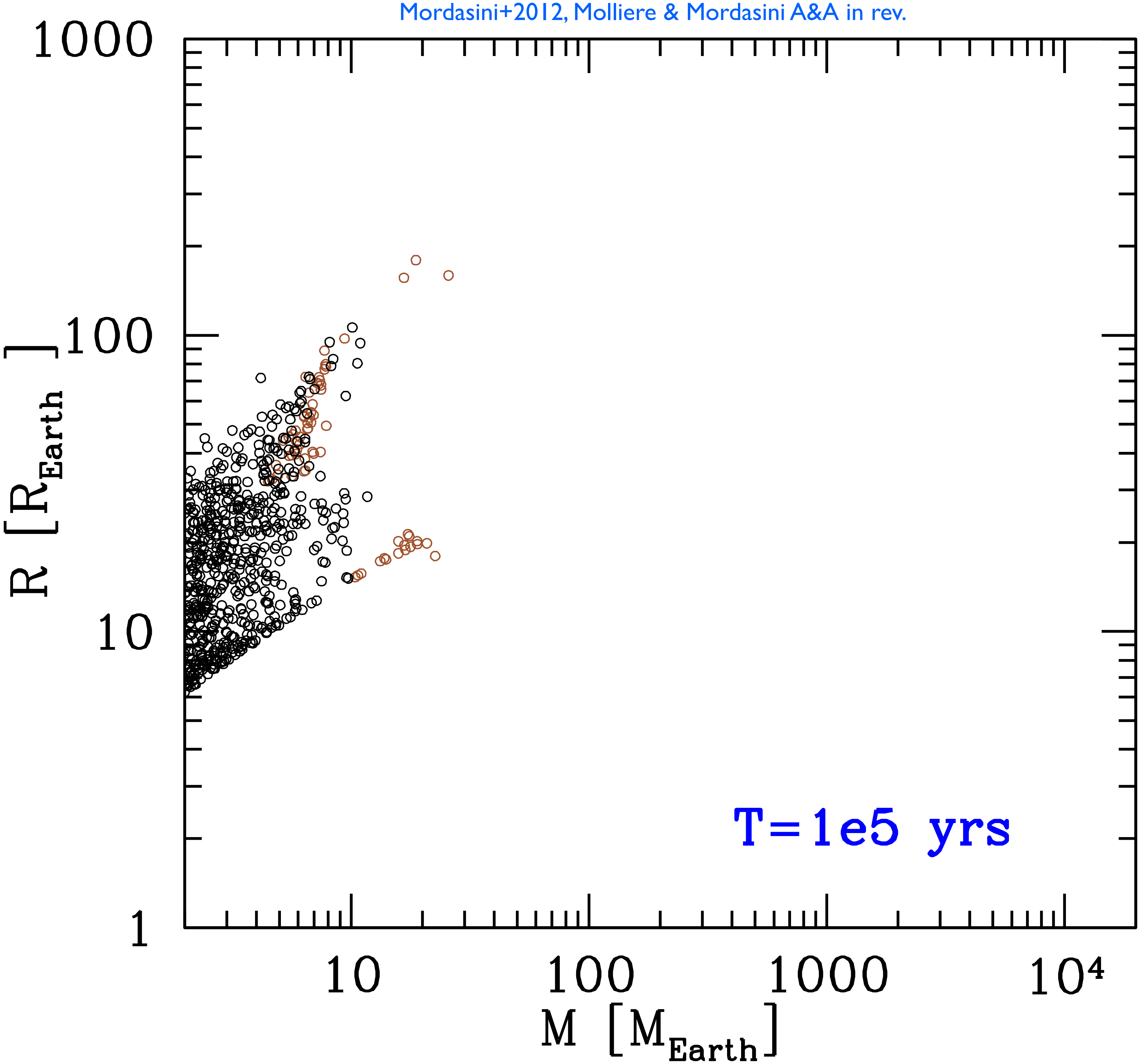


Jupiter atmo. p-T sequence



Population synthesis: Formation of M-R

Mordasini+2012, Molliere & Mordasini A&A in rev.



Fraction Z of solids (rest H/He)

Orange: $Z \leq 1\%$
Red: $1 < Z \leq 5\%$
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- Rapid collapse at ~0.2 M_J when $Z \approx 0.5$ (runaway gas accretion)
- After disk dispersal (T>10 Myrs), slow contraction.

Nominal Model. M_{star}=1 M_{sun}. a>0.1AU.
Non-isothermal Type I. Cold accretion. 1 embryo/disk

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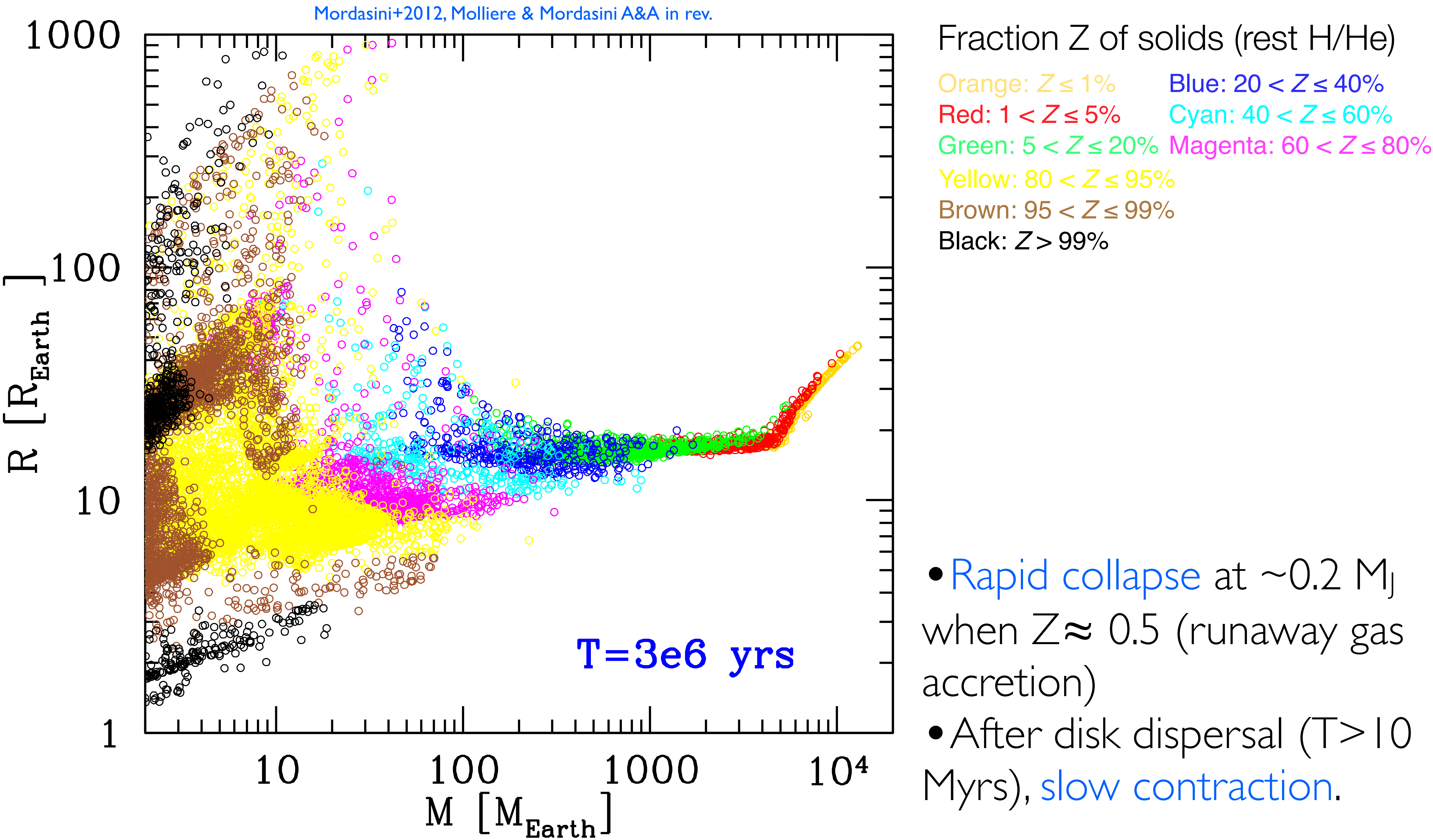

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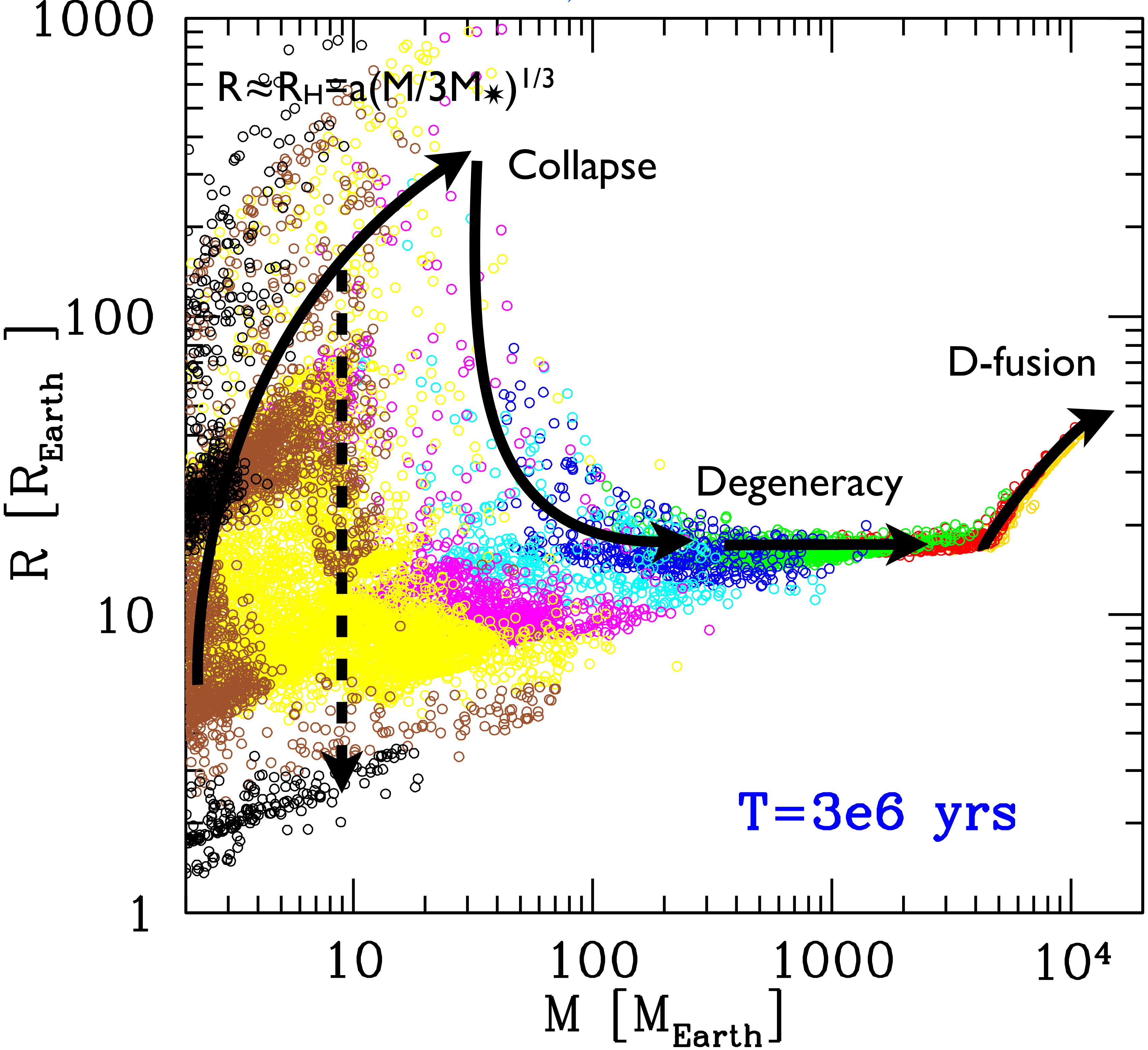

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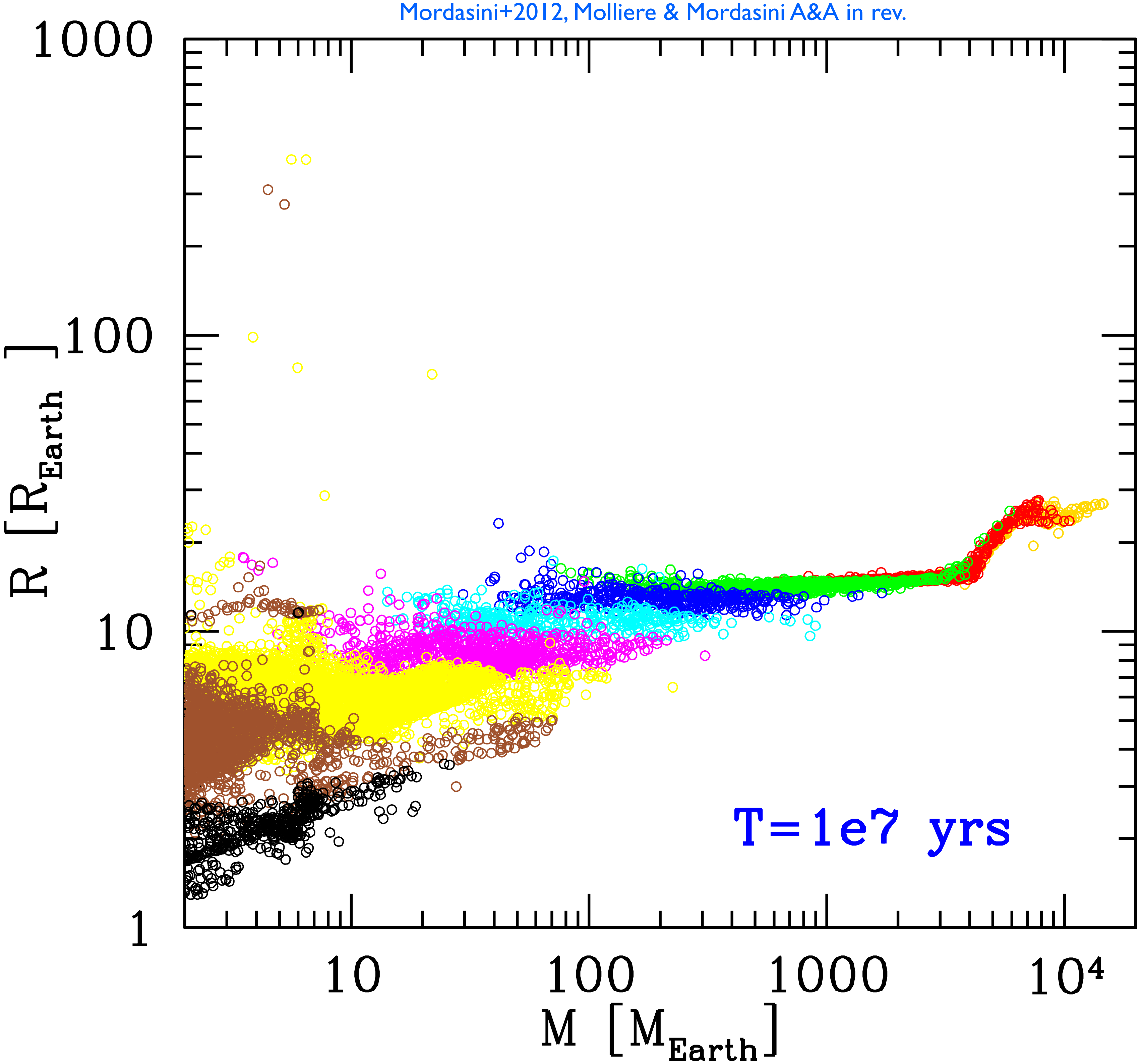

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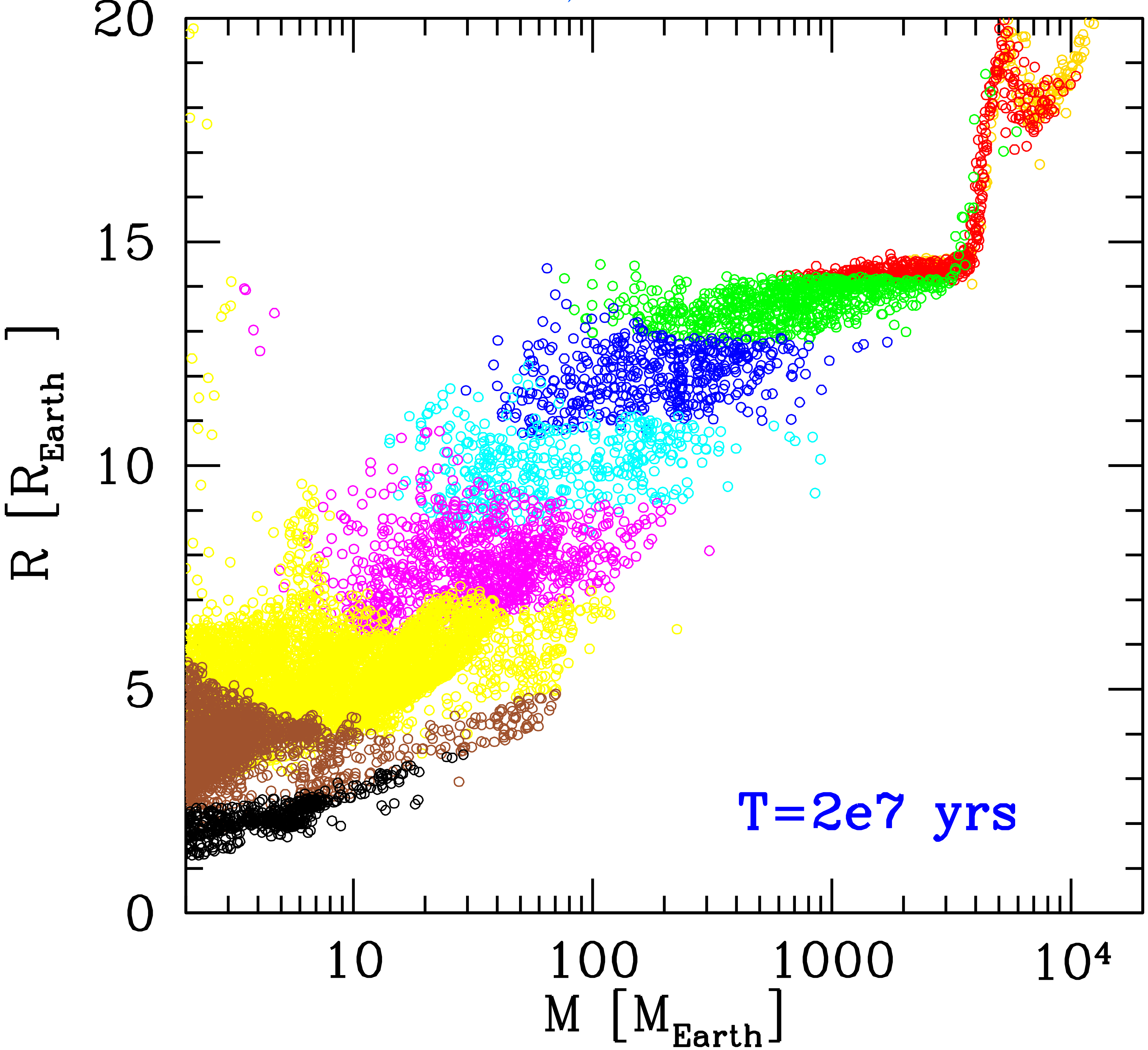

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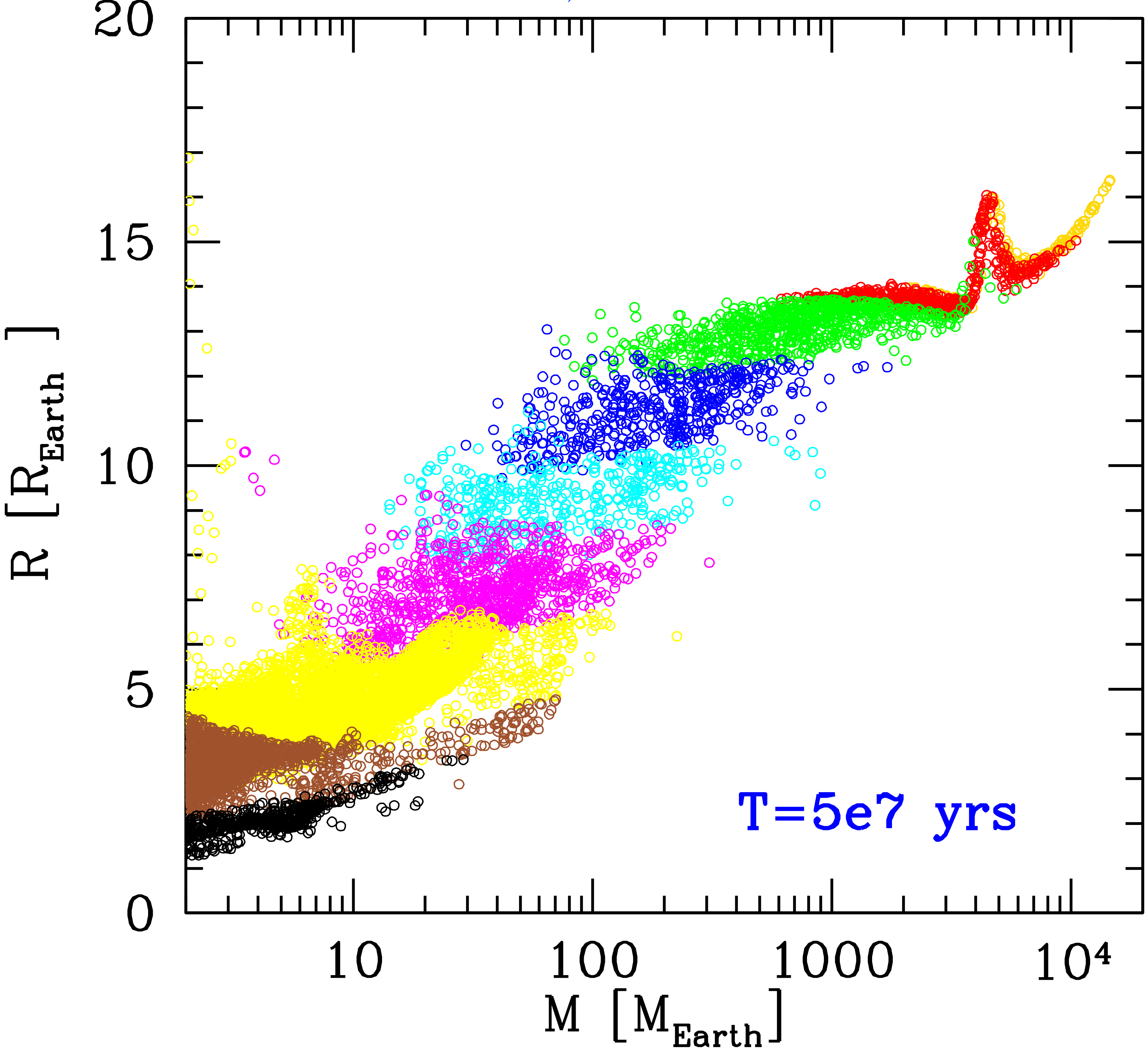

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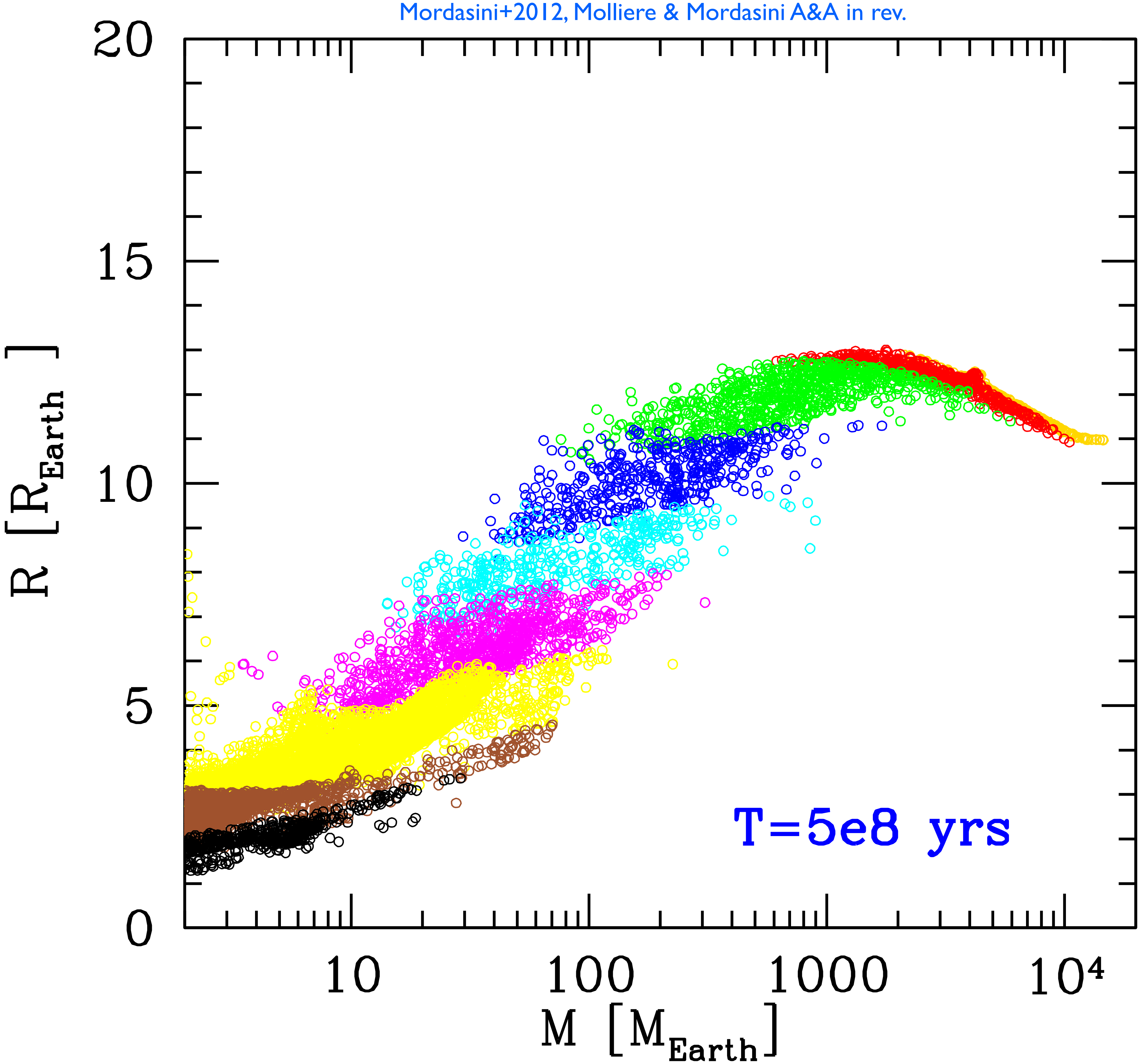

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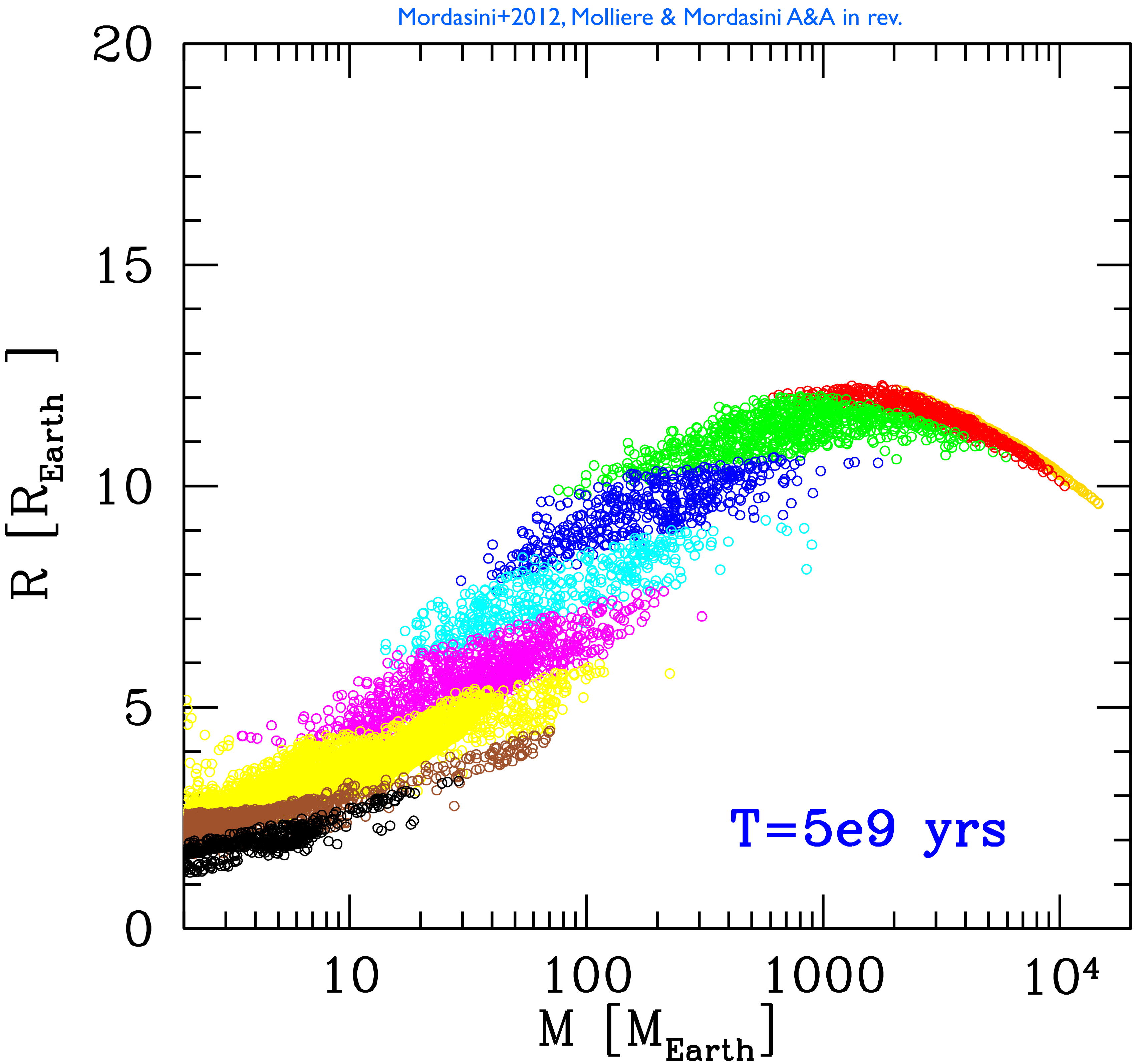

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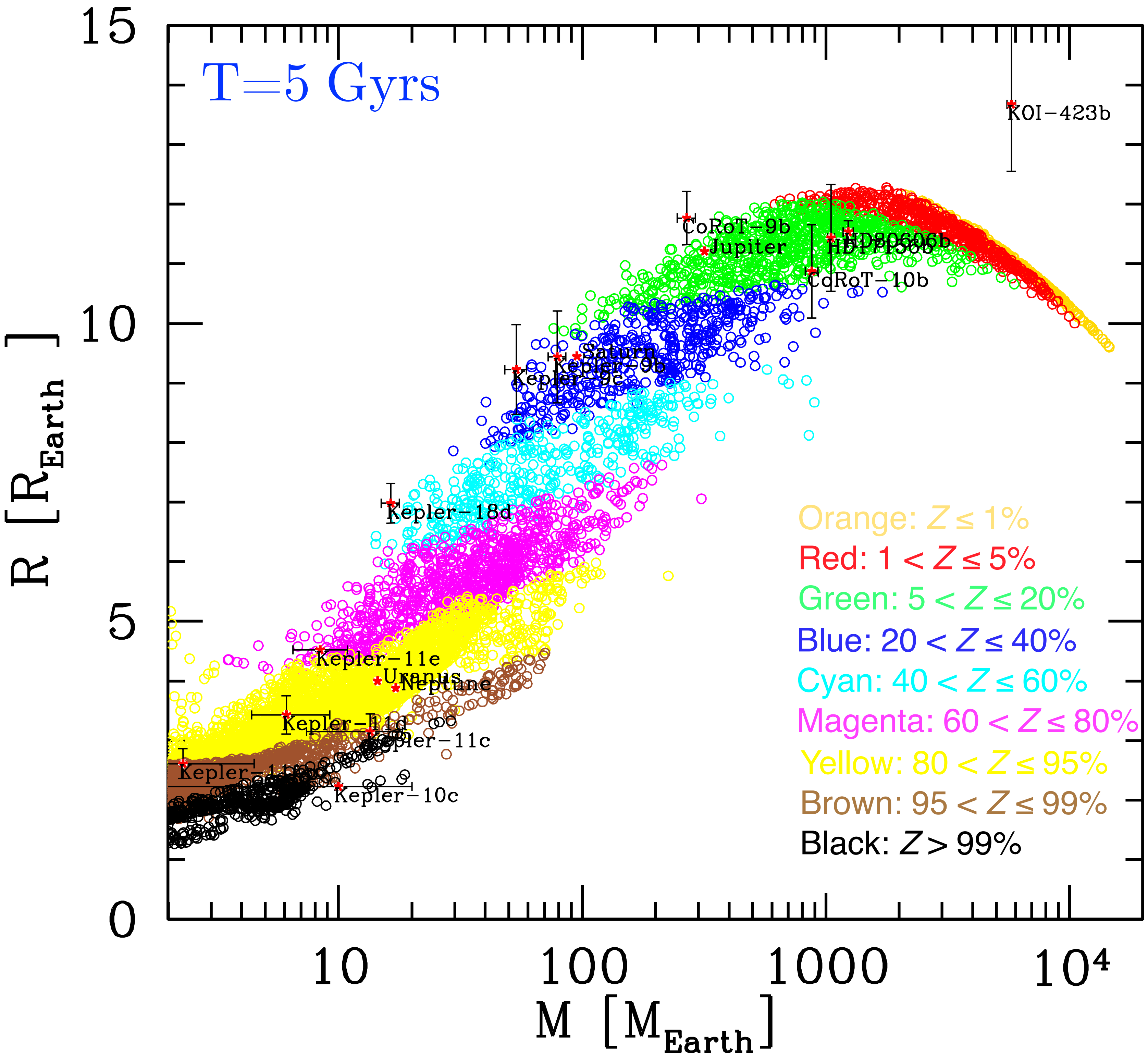
M-R diagram: comparison w. observations

Mordasini+2012b



All synthetic planets and all planets with 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
- Diversity in R at one M
- Comparison with observations fine except for KOI-423b. To be tested with future observation.
- Expect divergence in future at small masses (only H/He)!

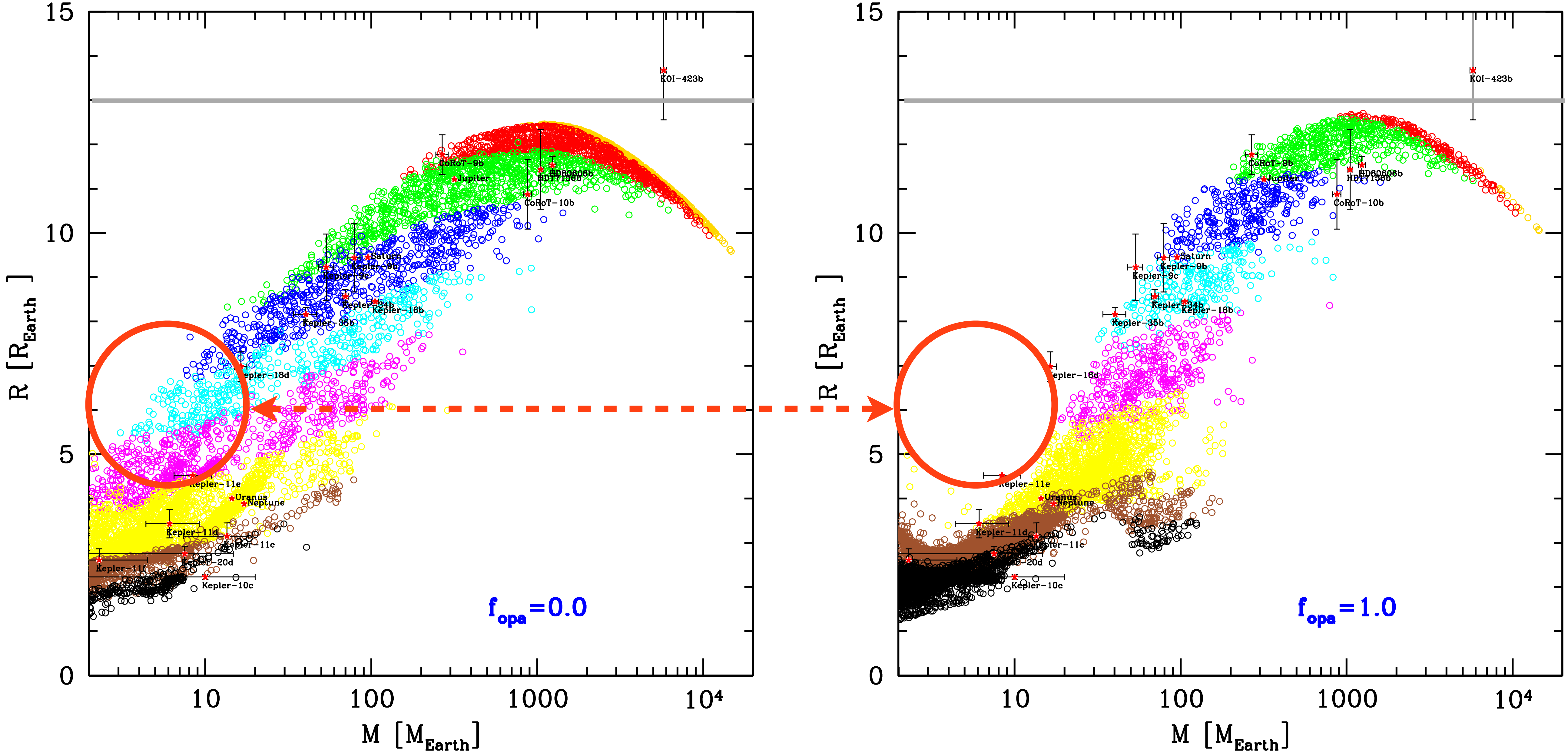
M-R diagram: effect of grain opacity

Efficiency of accretion of H/He by cores:
Controlled by opacity due to grains in the envelope during formation. Grains evolve.
Low opacity ⇨ high $M_{envelope}$ ⇨ large R.
High opacity ⇨ low $M_{envelope}$ ⇨ small R.
Podolak+2003, Movshovitz+2010, Hori & Ikoma 2010

M-R diagram: effect of grain opacity

Mordasini et al in rev.

Zero grain opacity | Full interstellar grain opacity



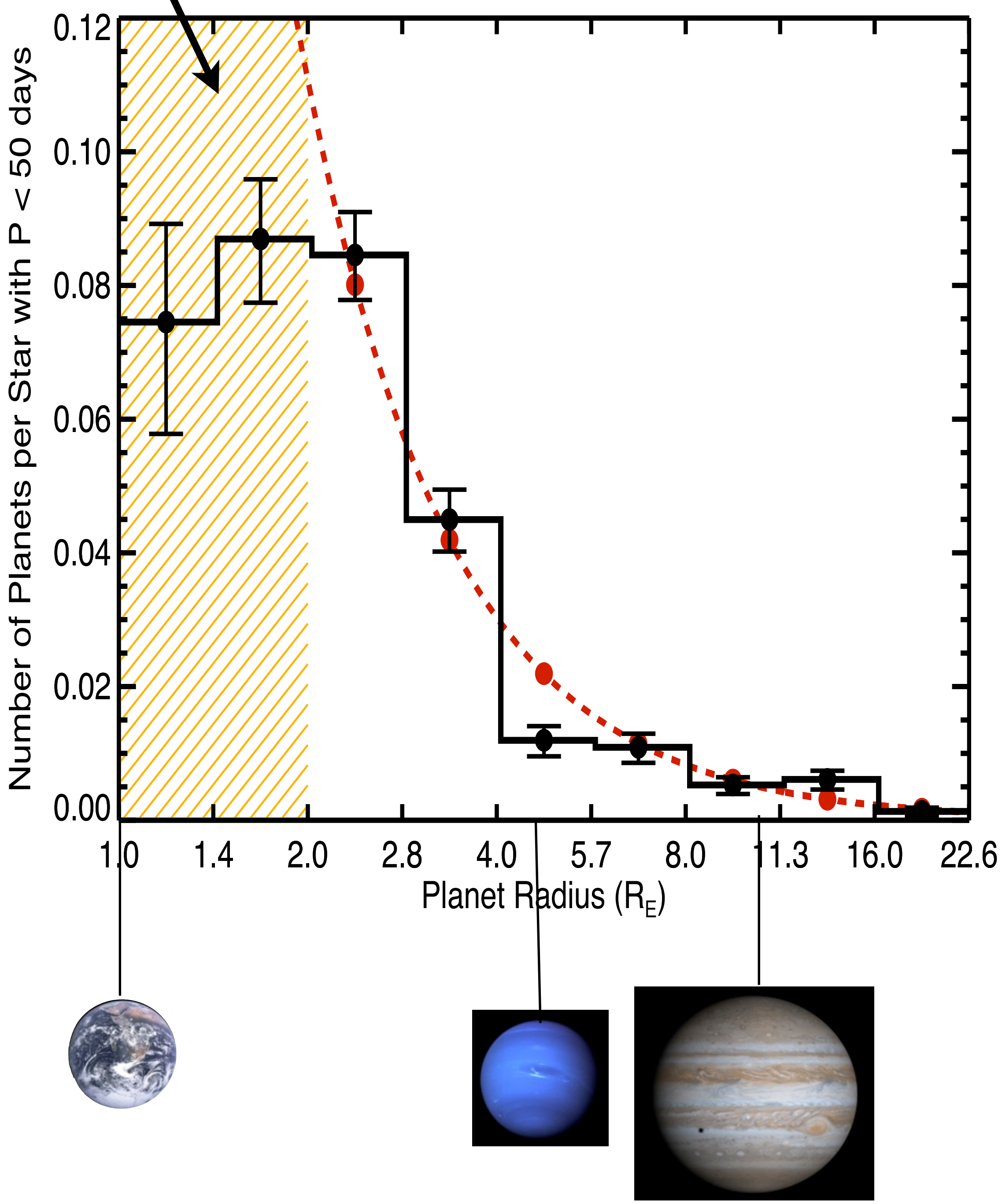
Link between ill known quantity important for formation and observations. Kepler-18d and Kepler-11e point towards small opacities.

Imprint of grain opacity on planetary mass-radius relationship.

Comparison: KEPLER radius distribution

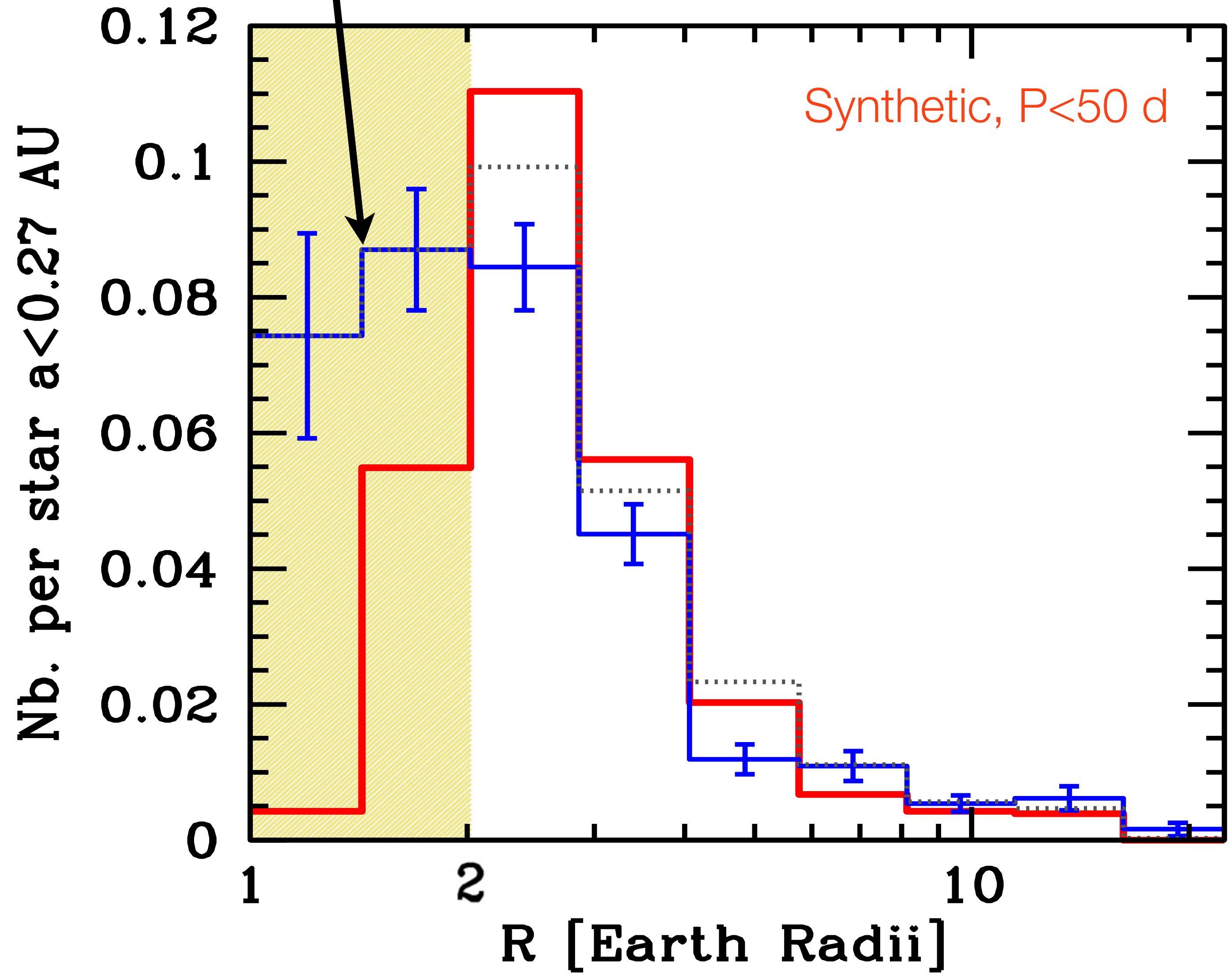
Incompleteness

Howard et al. 2011



Corrected for observational bias

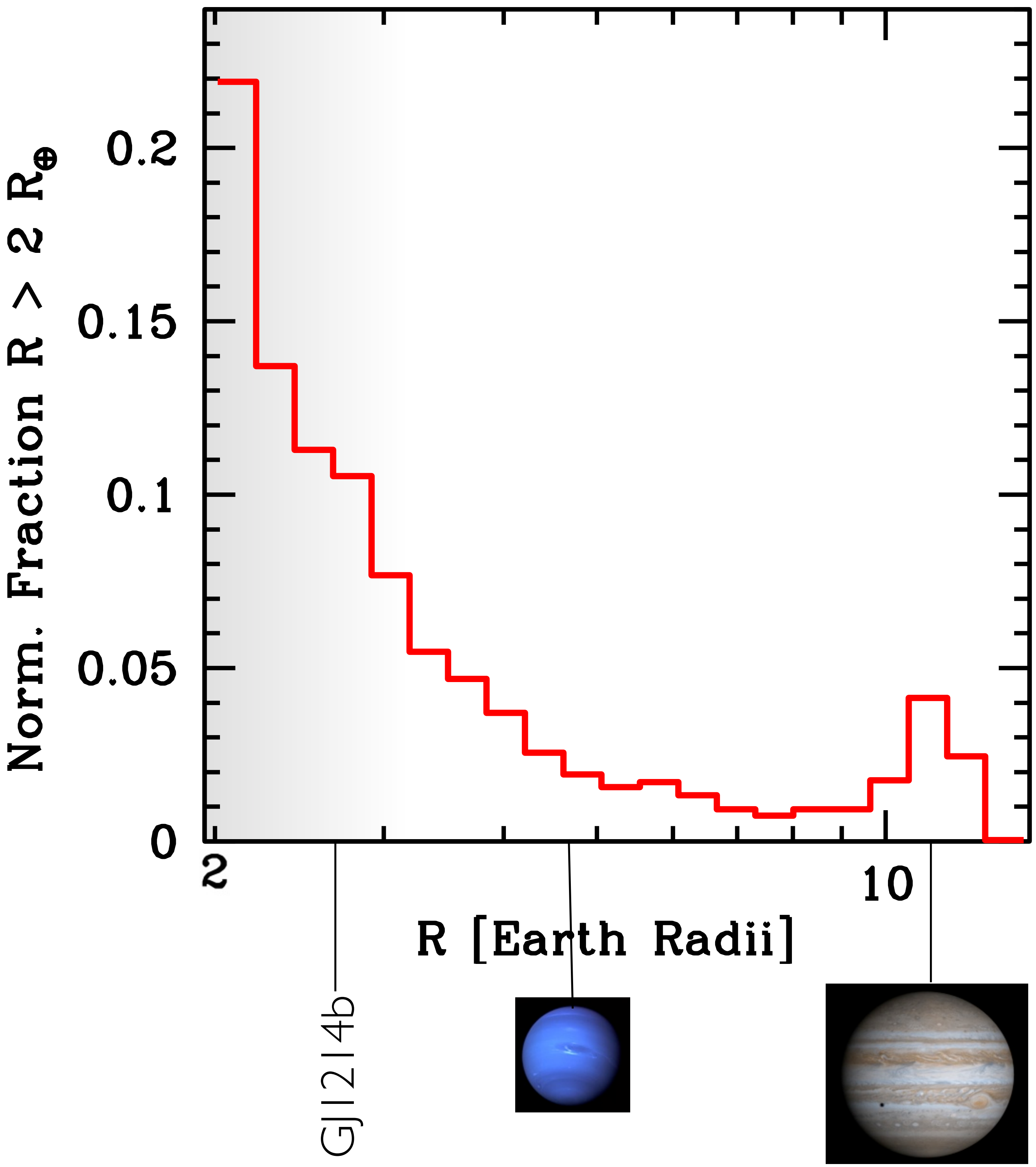
Not H/He atmospheres ?



- Tentative agreement for R> 2 R_E
  - Many low radii, Hot Jupiter 0.5-1%
  - Sensitive to type I migration model
- Divergence for R<2 R_E:
  - Low mass H/He planets have large radii.
  - Dividing line mini-Neptunes vs. super-Earth?

Bimodal planetary radius distribution

Mordasini+2012



all a, finer bins

- Radius distribution is *bimodal*
  (cf. Schlaufmann+2010, Wuchter2011)

- Peak at lowest radii. Most seeds don't grow much, and have large Z.

- Peak at ~ 1 R_J ⇨ Giant planets have all approx. *the same radius independent of mass* (degeneracy!)

- Prediction: Kepler should detect the second, local maximum at ~1 R_J (except ....)

Summary

1) Added self-consistently evolution to c.a. formation model, giving radius and luminosity besides a, M, e.

2) Calculated population wide M-R relationship.

3) Compared with observation, finding good agreement for the general shape. Many imprints of formation.

4) Calculated planetary radius distribution. Bimodal, w. strong increase to small R, and second maximum at ~1 R_J.

5) Compared with Kepler R distribution. Similar general shape. We predict the ~1 R_J maximum to be found in future.

C. Mordasini, Y. Alibert, C. Georgy, K.-M. Dittkrist, H. Klahr, & T. Henning A&A accepted, arXiv 1206.3303
C. Mordasini, Y. Alibert, H. Klahr, & T. Henning A&A accepted, arXiv 1206.6103