FORMATION OF CLOSE-IN PLANETS IN AN EVOLVING DISC WITH N-BODY SIMULATIONS

Masahiro Ogihara

(National Astronomical Observatory of Japan)

Acknowledgments:

Eiichiro Kokubo (NAOJ), Takeru Suzuki (Univ. Tokyo), Alessandro Morbidelli (OCA)

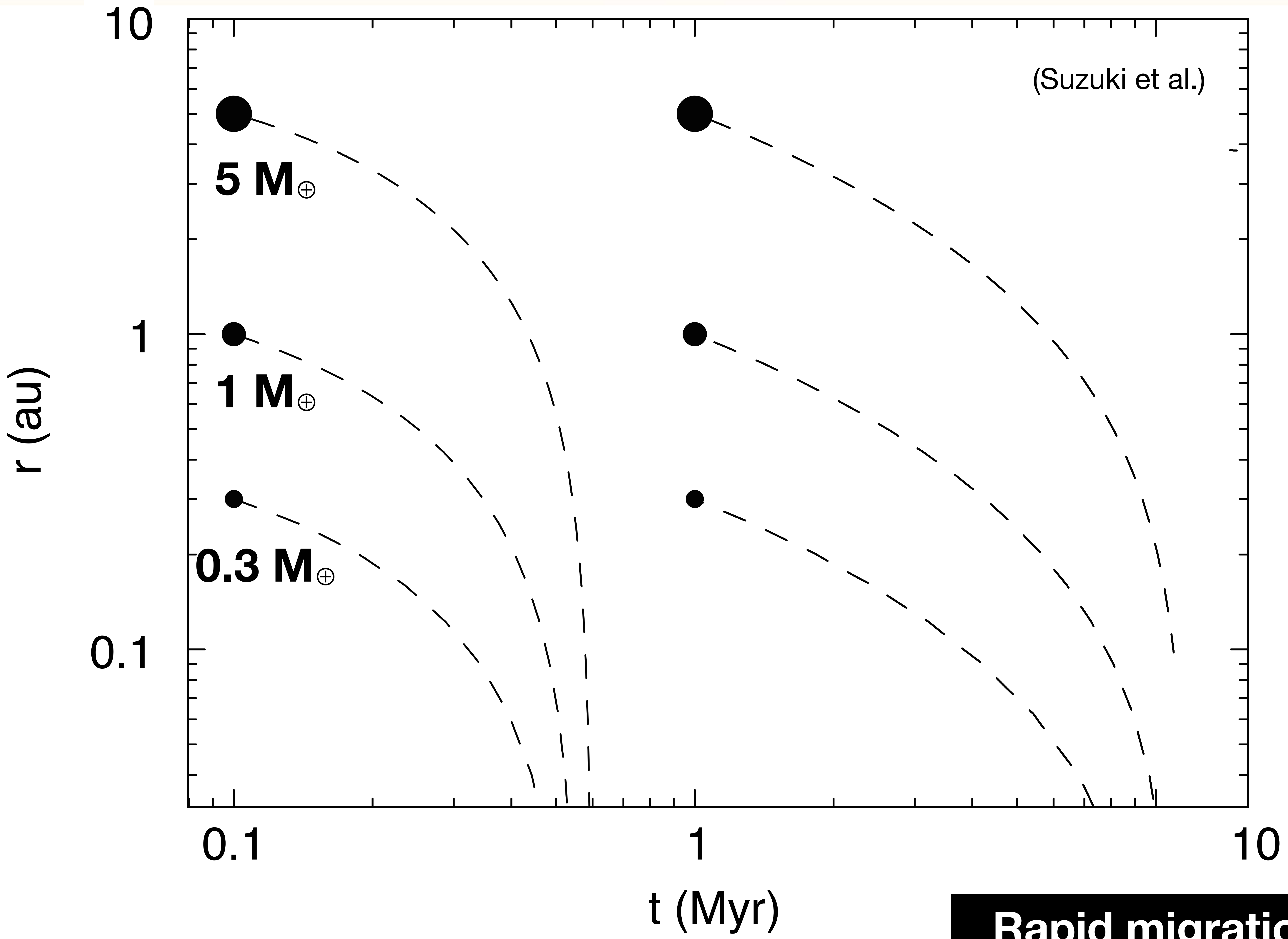
see also Ogihara et al. (2018, A&A)

国立天文台 NAOJ National Astronomical Observatory of Japan

東京大学 THE UNIVERSITY OF TOKYO

Observatoire de la CÔTE d'AZUR

Barrier in planet formation: Type I migration



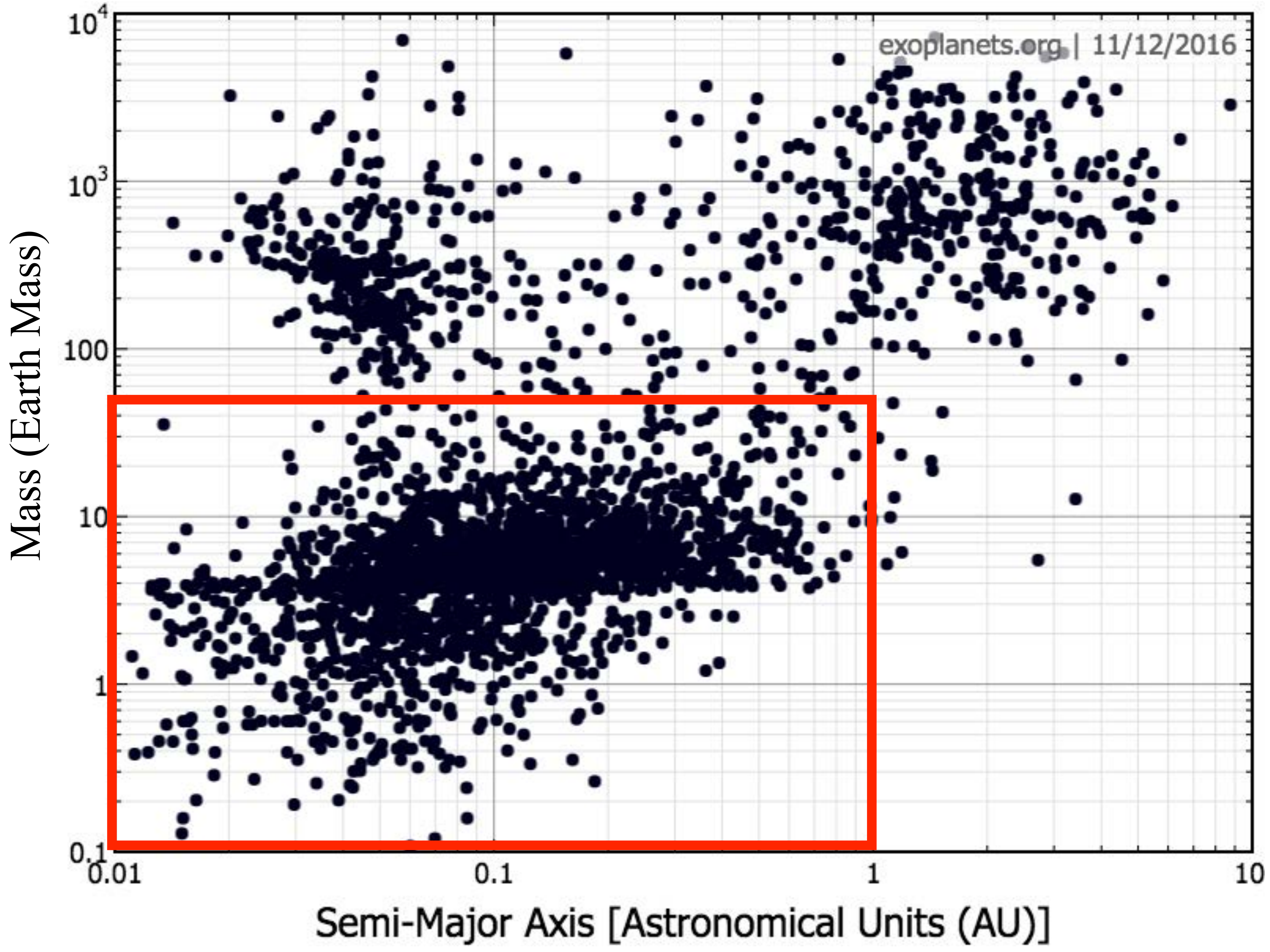
Rapid migration may cause several problems

Key questions in this talk

Q1: Is type I migration really problematic in close-in super-Earth formation?

Q2: If so, how can we overcome the migration problem?

Close-in super-Earths



Close-in super-Earths

- **2401 planets** (confirmed)

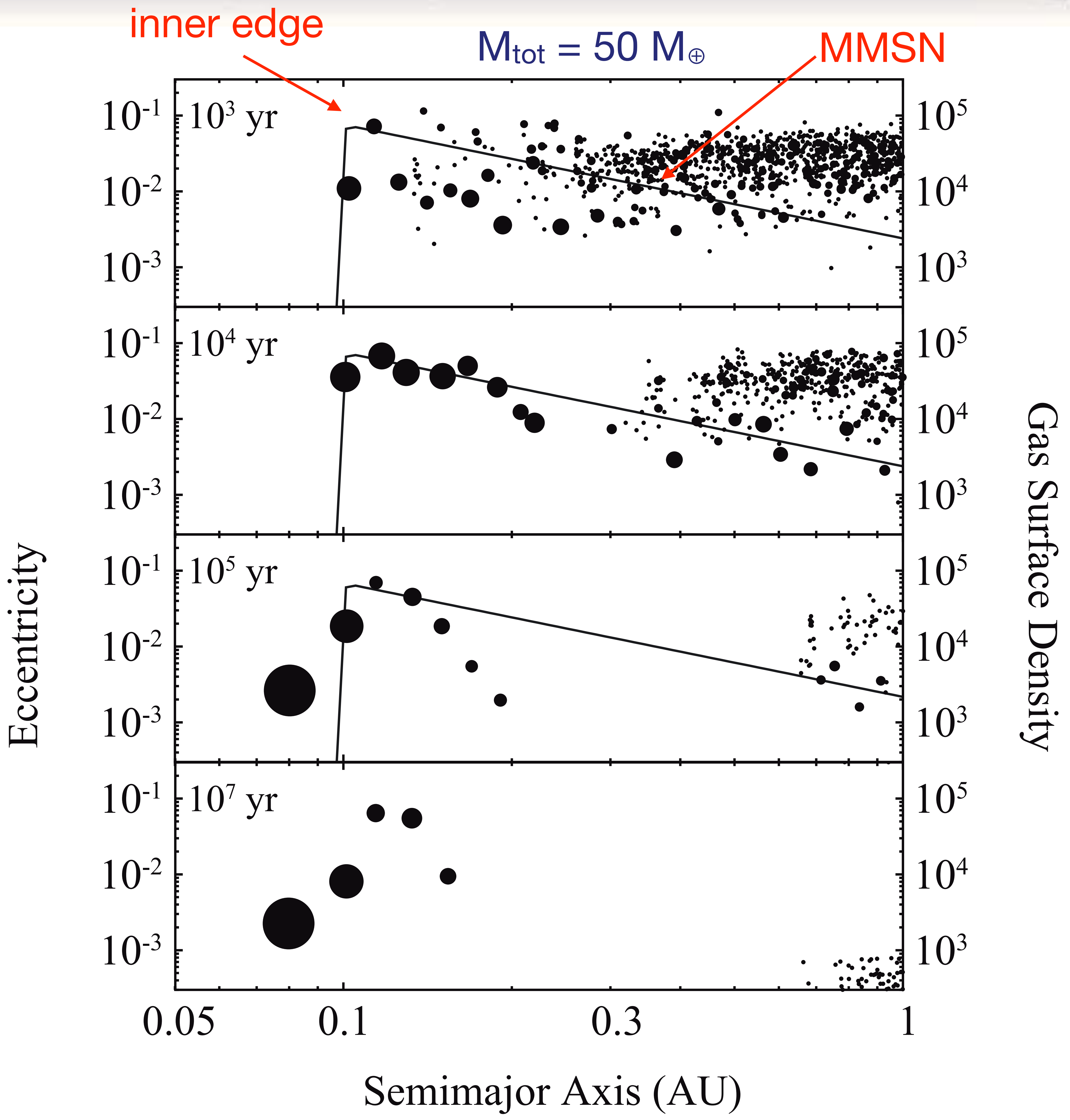
Multiple close-in super-Earth systems (*N*≧2)

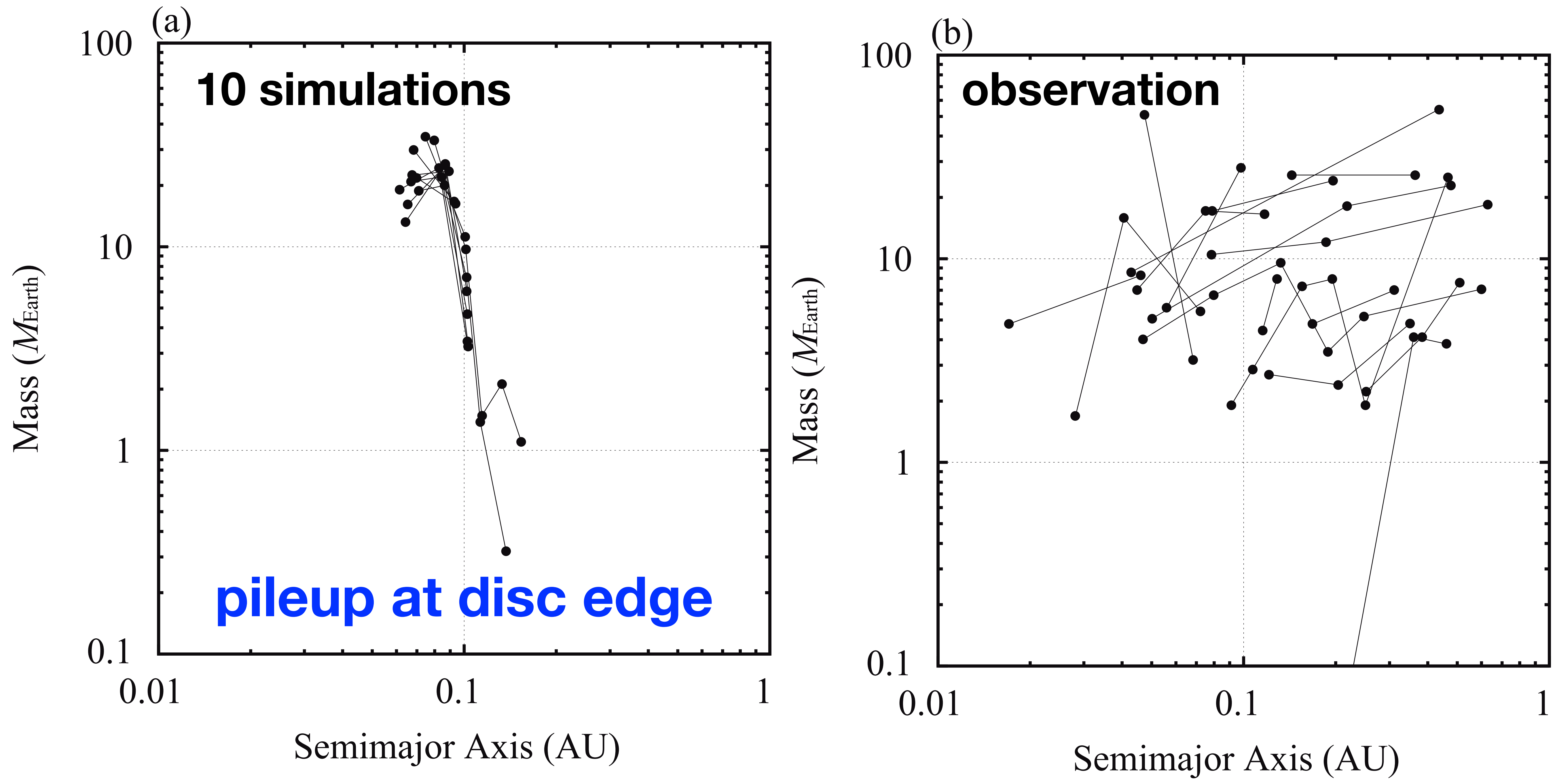
- **432 systems**
- **1082 planets** (confirmed)

as of Aug. 2017

Formation of super-Earths in a power-law disc

(Ogihara, Morbidelli, Guillot 2015)





$$t_{acc} \sim 10^3 \left(\frac{\Sigma_d}{150\ \mathrm{g/cm^3}}\right)^{-1} \left(\frac{a}{0.3\ \mathrm{au}}\right)^{27/10} \left(\frac{M}{M_\oplus}\right)^{1/3} \mathrm{yr}$$

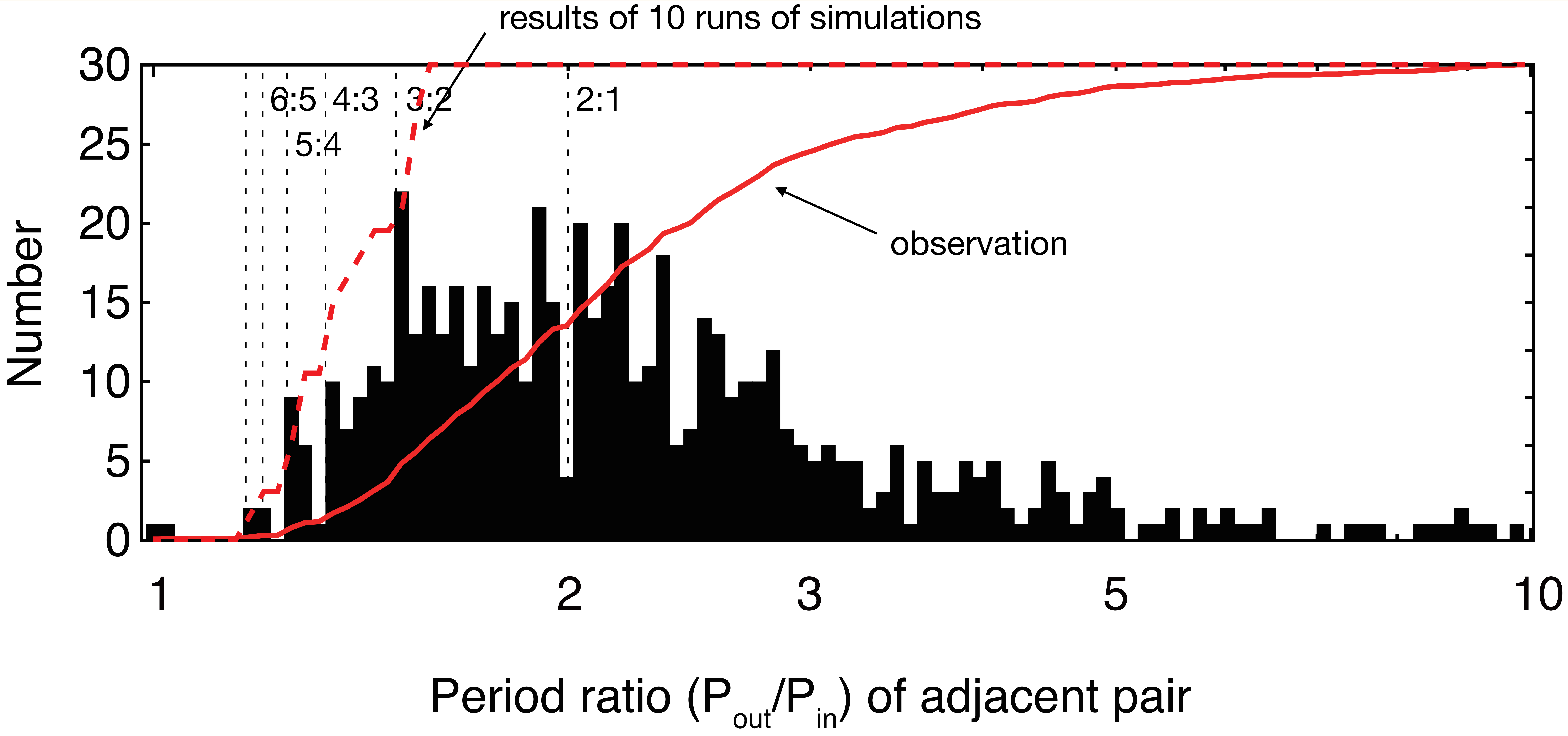
short growth timescale

↓

rapid type I migration

$t_{mig} \sim 10^4$ yr

Formation of super-Earths in a power-law disc



- observation: not in MMRs (mean motion resonances)
- simulation: compact systems in MMRs (←rapid inward migration)

Key questions in this talk

Q1: Is type I migration really problematic in close-in super-Earth formation?

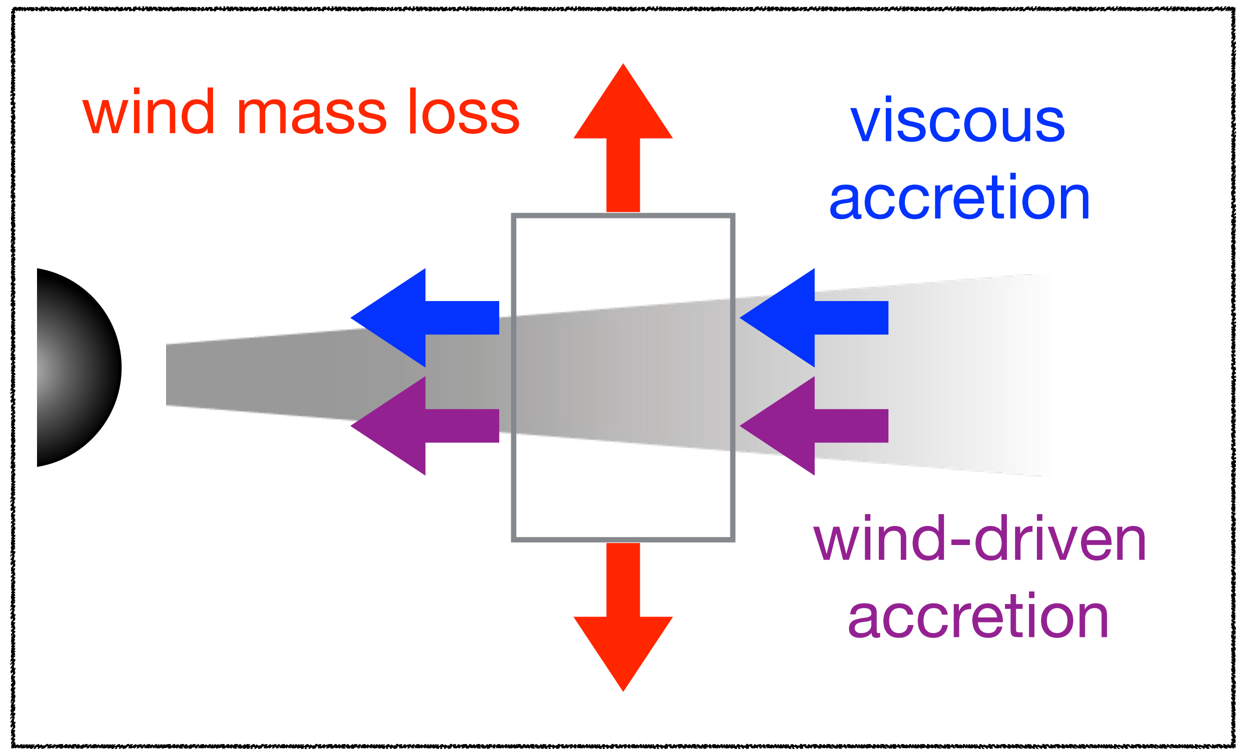
➡ **Yes. Due to rapid inward migration, results of simulations are inconsistent with observed distributions (e.g., period ratio).**

Q2: If so, how can we overcome the migration problem?

➡ **Disc model.**

Disc evolution including disc winds

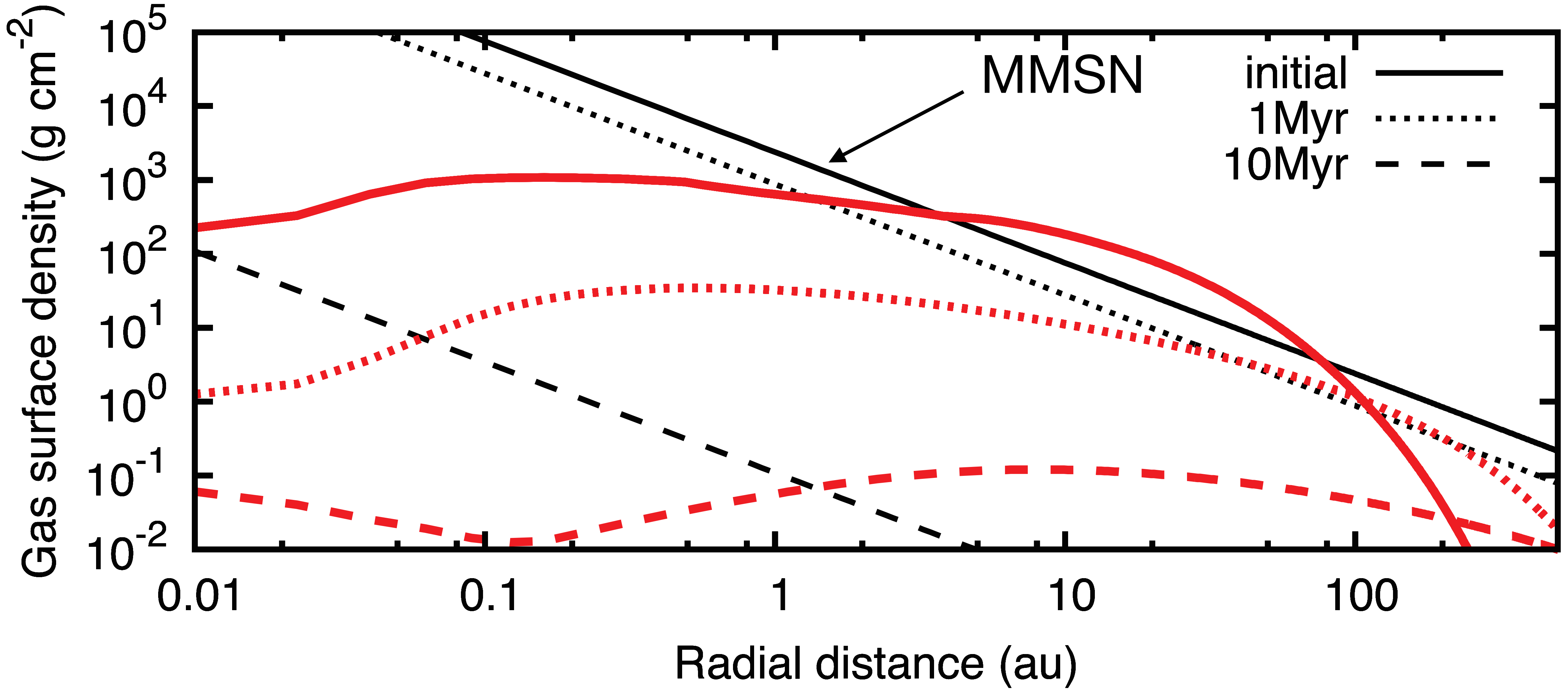
(Suzuki, Ogihara, Morbidelli et al. 2016)



MHD simulation (by T. Suzuki; X. Bai)

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left\{ \frac{2}{r\Omega}\left[\frac{\partial}{\partial r}(r^2 \Sigma \alpha c_s^2) + r^2 \alpha_w \frac{\Sigma}{\sqrt{\pi} H} c_s^2 \right] \right\} + C_w \frac{\Sigma}{\sqrt{\pi} H} c_s$$

viscous accretion (turbulence-driven) | wind-driven accretion (magnetic braking) | wind mass loss



disc profiles can be altered from MMSN (r < 1 au)

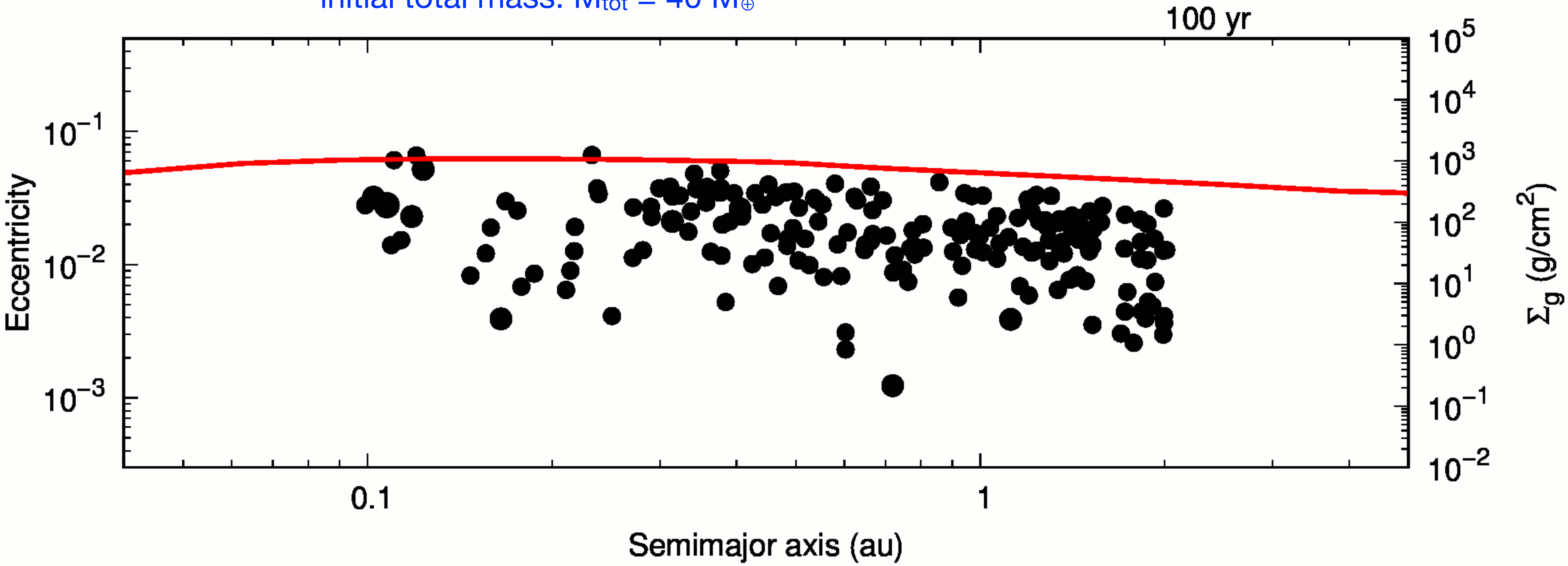
- flat surface density slope
- decrease in density

type I migration would change

Formation of super-Earths including disc winds

(Ogihara, Kokubo, Suzuki, Morbidelli 2018)

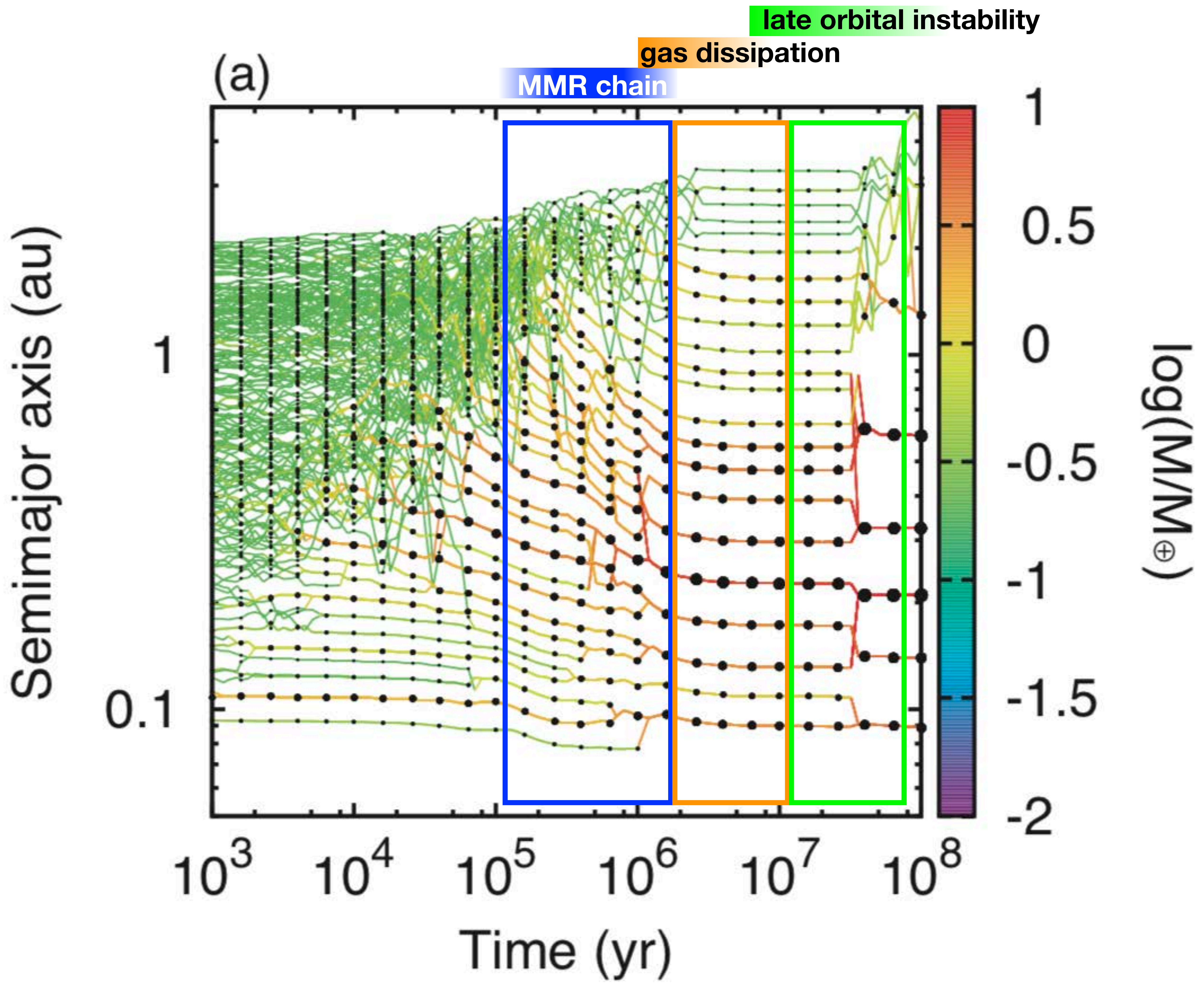
initial total mass: $M_{tot} = 40\ M_\oplus$



Planets do not undergo significant migration

Formation of super-Earths including disc winds

(Ogihara, Kokubo, Suzuki, Morbidelli 2018)



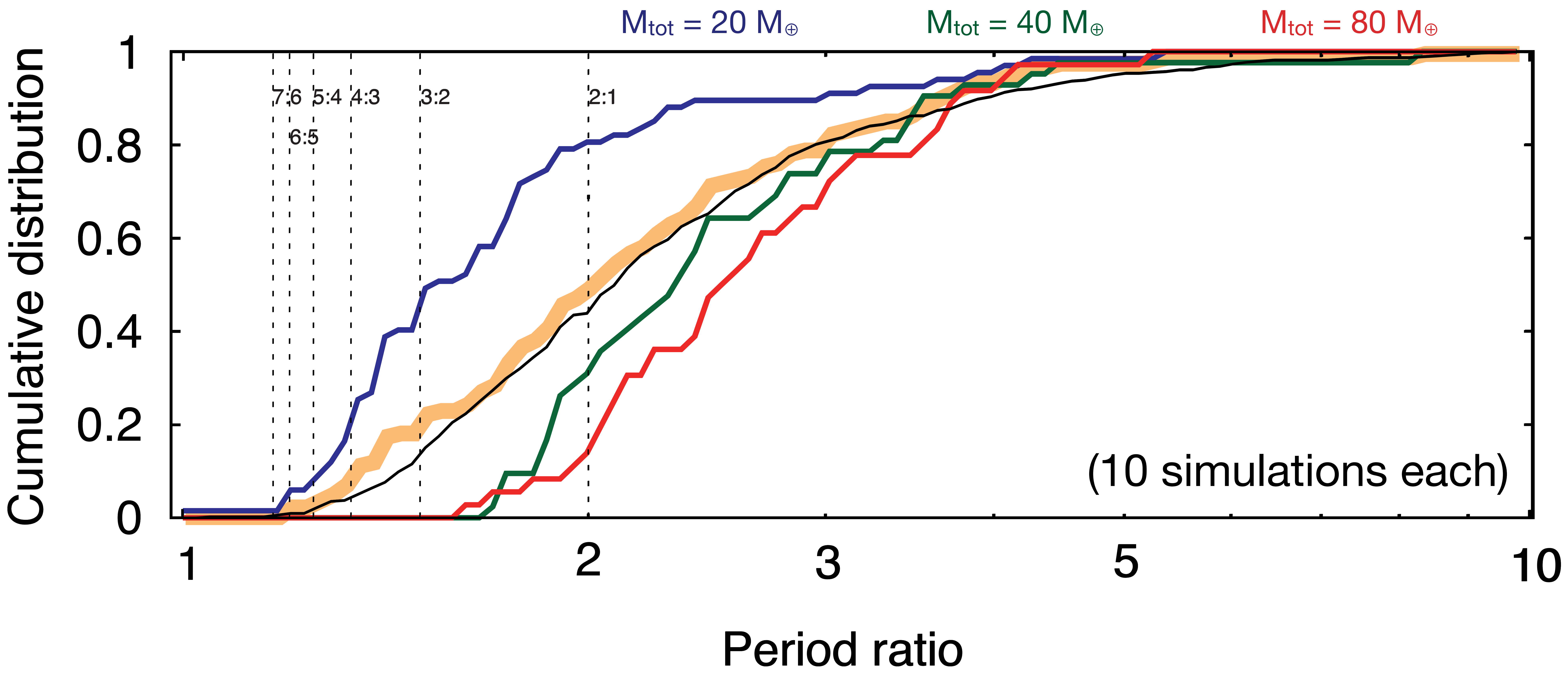
FORMATION PROCESSES

- slow migration → formation of MMRs
- gas dissipation (~a few Myr)
- instability→giant impacts

not in mean-motion resonances

Formation of super-Earths including disc winds

(Ogihara, Kokubo, Suzuki, Morbidelli 2018)



Observed distribution can be reproduced when the migration is slow

Key questions in this talk

Q1: Is type I migration really problematic in close-in super-Earth formation?

➡ Yes. Due to rapid inward migration, results of simulations are inconsistent with observed distributions (e.g., period ratio).

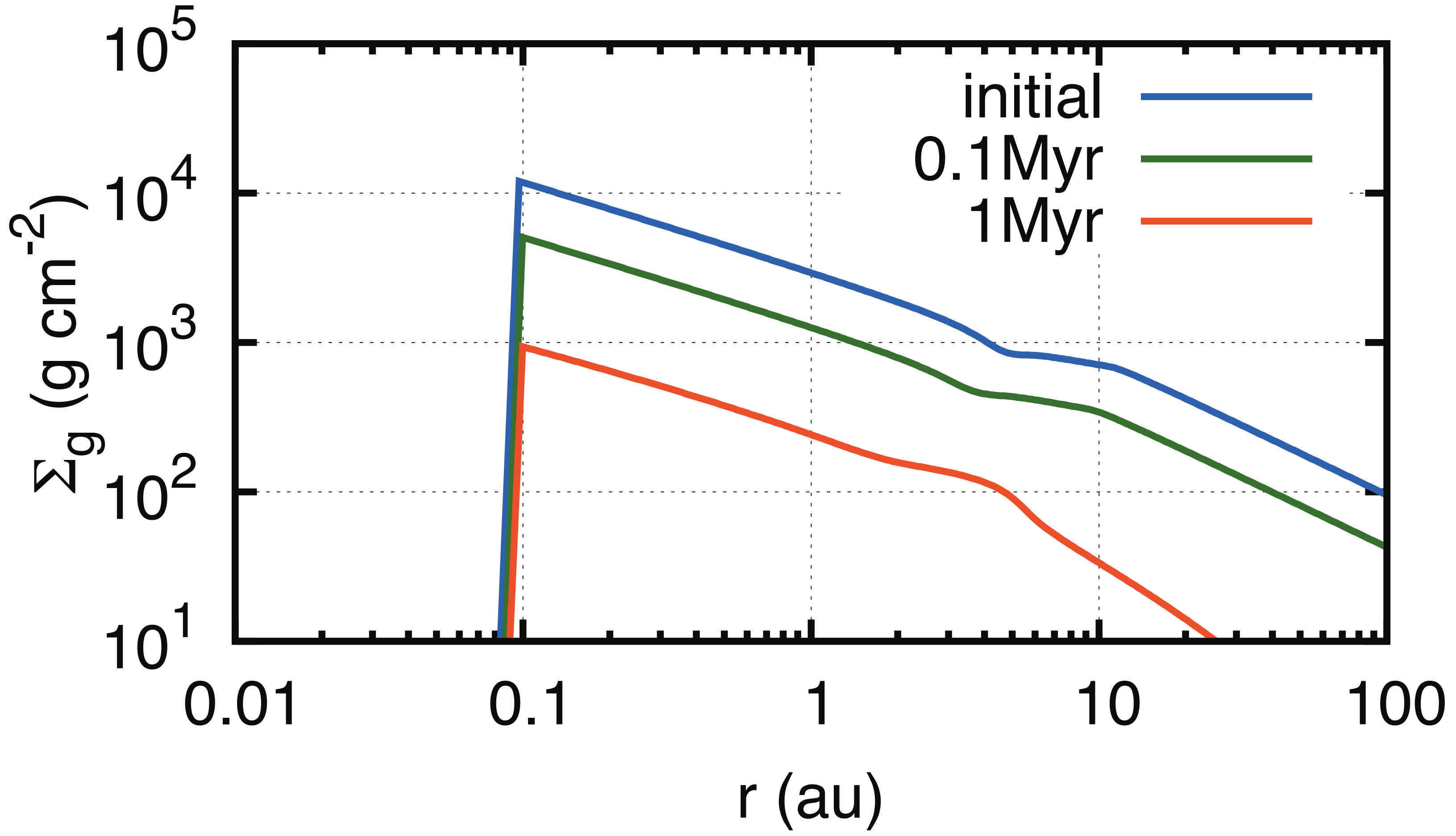
Q2: If so, how can we overcome the migration problem?

➡ Type I migration can be slowed down if the disc is depleted ($\rightarrow$slope, Σ_g) in the close-in region

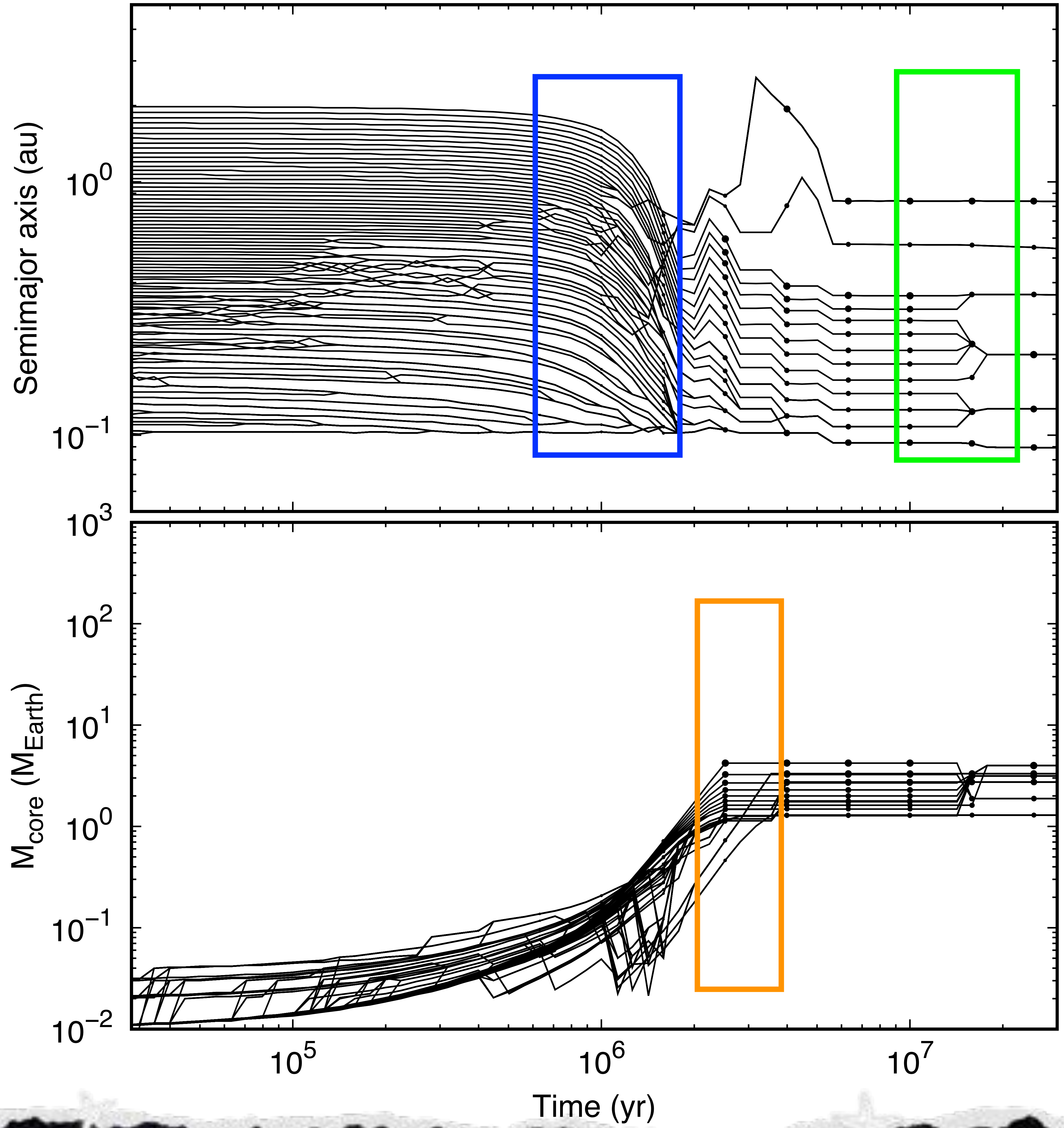
Comment on different approach

❏ **Model**

- disc model (Bitsch et al. 2015)



- initial total solid: 1$M_\oplus$
- pebble accretion



- **Slow migration** (~Myr)
- Planets reach **SE-mass** in the late phase
- Planets are **not in MMRs**

(see also Lambrechts et al. 2019)

Slow migration is favored

Summary

❑ N-body simulations of formation of close-in super-Earths

❑ Rapid type I migration results in compact systems in MMRs

❑ If the gas density is depleted in the close-in region (e.g., Suzuki et al. 2016), type I migration can be slowed down

❑ Observed properties of close-in super-Earths can be reproduced (ie, not in MMRs)

see also Ogihara et al. (2018, A&A)