Tactful Accretion: Considering Constraints in the Grand Tack Model

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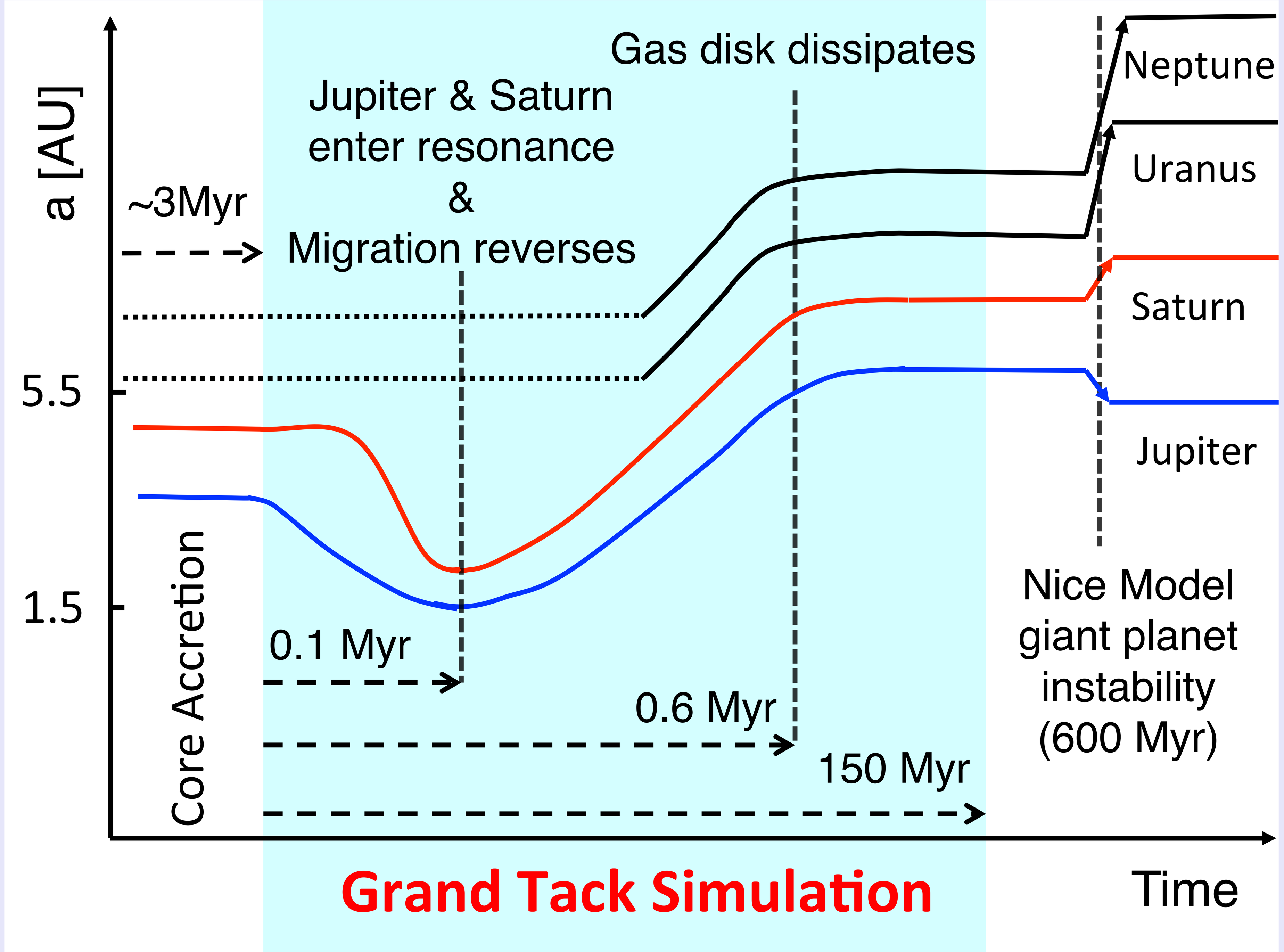
Take Away Message

The Grand Tack model robustly reproduces the low mass of Mars even as these two parameters are varied: (1) initial embryo mass M_e and (2) ratio of the amount of mass in embryos to the amount of mass in planetesimals $\Sigma M_e{:}\Sigma M_p$

Larger initial embryo masses M_e form Mars faster and lead to a larger variance in the last giant impact time and the size of the late veneer.

Higher mass ratios $\Sigma M_e{:}\Sigma M_p$ result in later giant (Moon-forming) impacts and smaller late veneers.

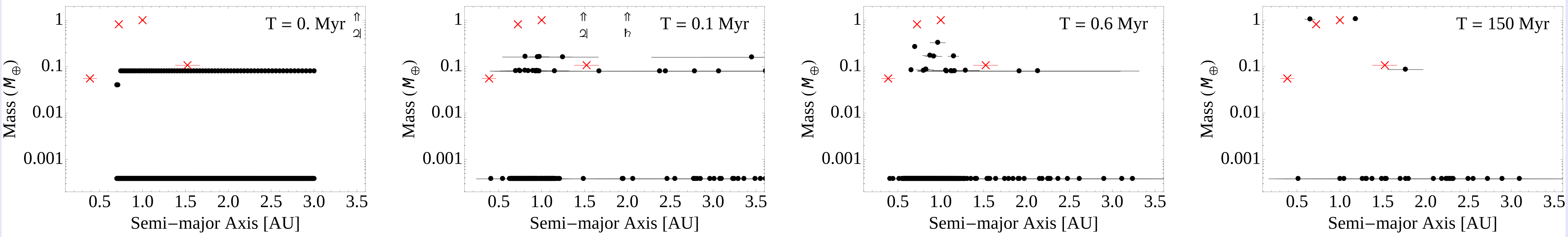


Introduction

The inward and outward migration of Jupiter and Saturn, the Grand Tack, creates a truncated disk of embryos and planetesimals. The evolution of this disk broadly reproduces the terrestrial planets including a small Mars. Expanding from Walsh et al. (2011), we use N-body simulations to explore a variety of oligarchic growth regimes in the inner Solar System by adjusting the following parameters:

- Mass of the initial embryos M_e – If the oligarchic growth process is more efficient or the growth period is longer before interruption by the Grand Tack, then more massive embryos are created.
- Ratio of the amount of mass in embryos to the mass in planetesimals $\Sigma M_e{:}\Sigma M_p$ – The amount of total mass in embryos relative to the total mass in planetesimals is possibly a reflection of the severity of collisional grinding during the oligarchic growth phase (Levison DPS 2012). More severe collisional grinding increases the mass in embryos relative to planetesimals.

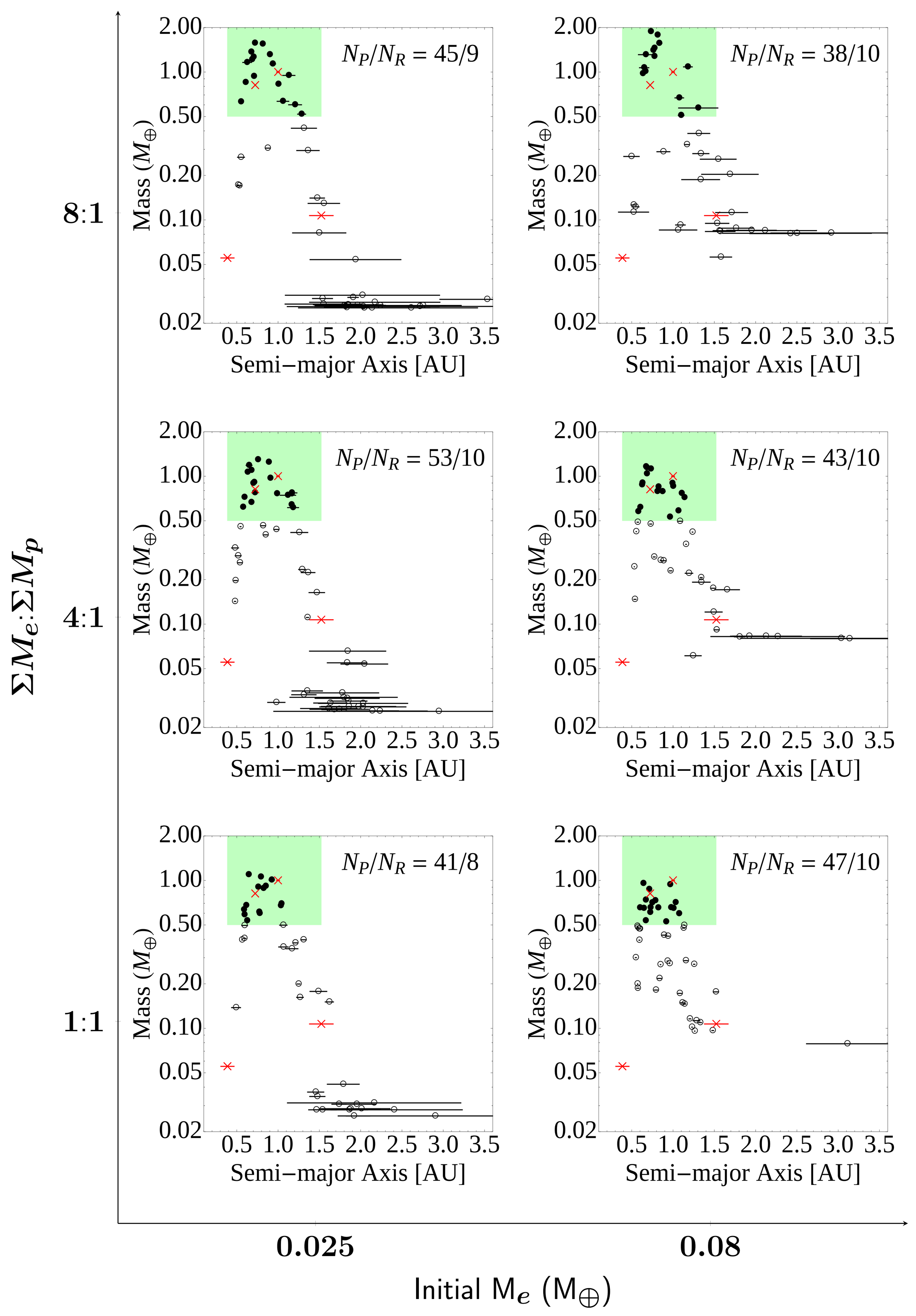
Example of a Grand Tack simulation of an evolving terrestrial disk



This example has initial conditions: mass embryos $M_e = 0.08\ M_\oplus$ and a ratio of the sums of the mass in embryos to the mass in planetesimals $\sum M_e{:}\sum M_p = 8{:}1$.

Mass and Orbit Distributions of the Final Planets

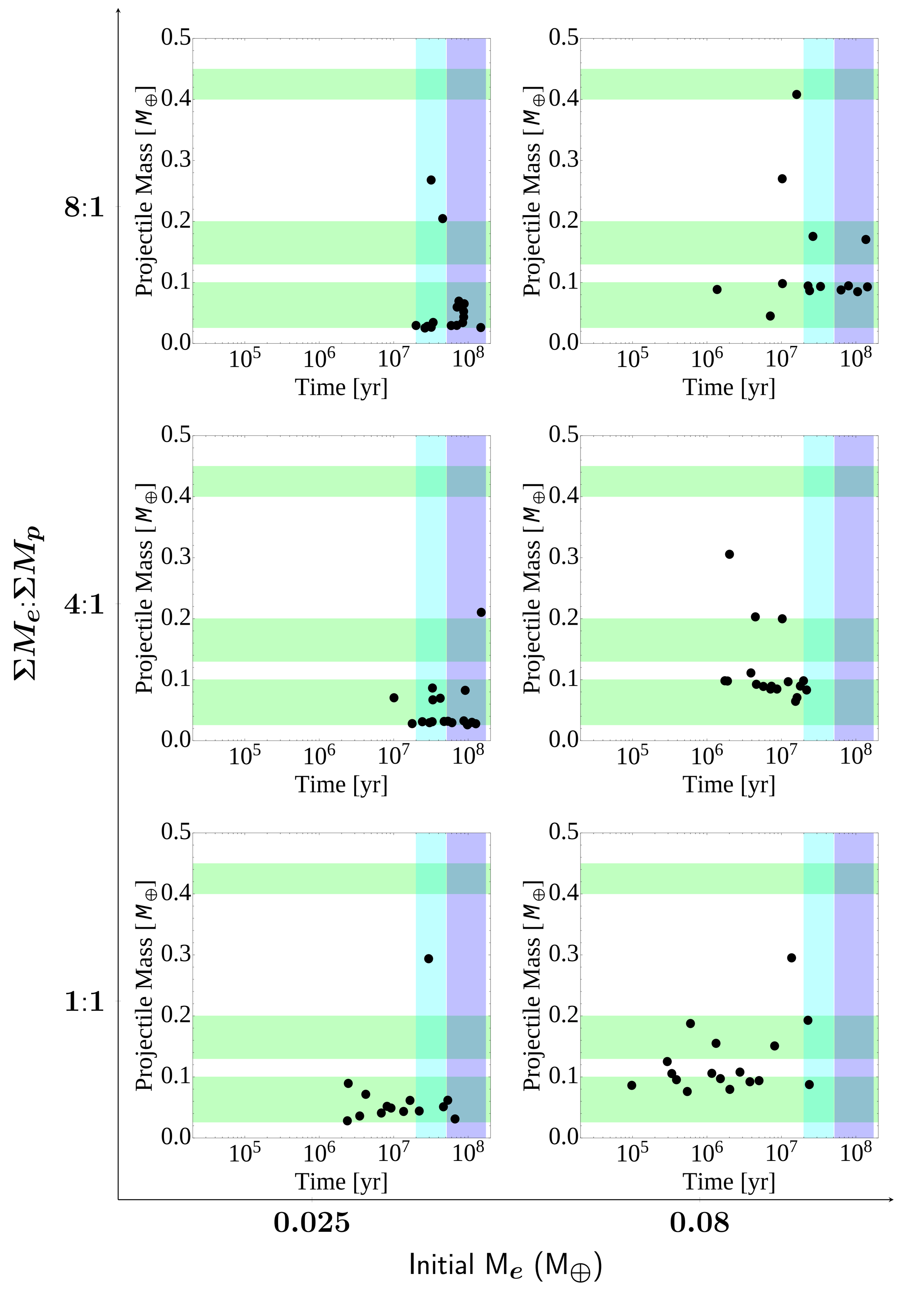
These figures show the mass and semi-major axis of every terrestrial planet in each suite of simulations. Each suite corresponds to different initial conditions. A green box indicates the Earth analog region. For reference, N_P/N_R is the number of planets over the number of runs (simulations) in that suite.



- All simulation suites robustly create an arcing mass distribution consistent with the inner Solar System
- Almost all systems have 4 to 5 planets including 2 Earth analogs
- All suites struggle to create true Mercury analogs
- Final planet mass increases with larger $\Sigma M_e{:}\Sigma M_p$
- Better Mars analogs exist with larger initial M_e

Mass and Time of the Last Giant Impactors

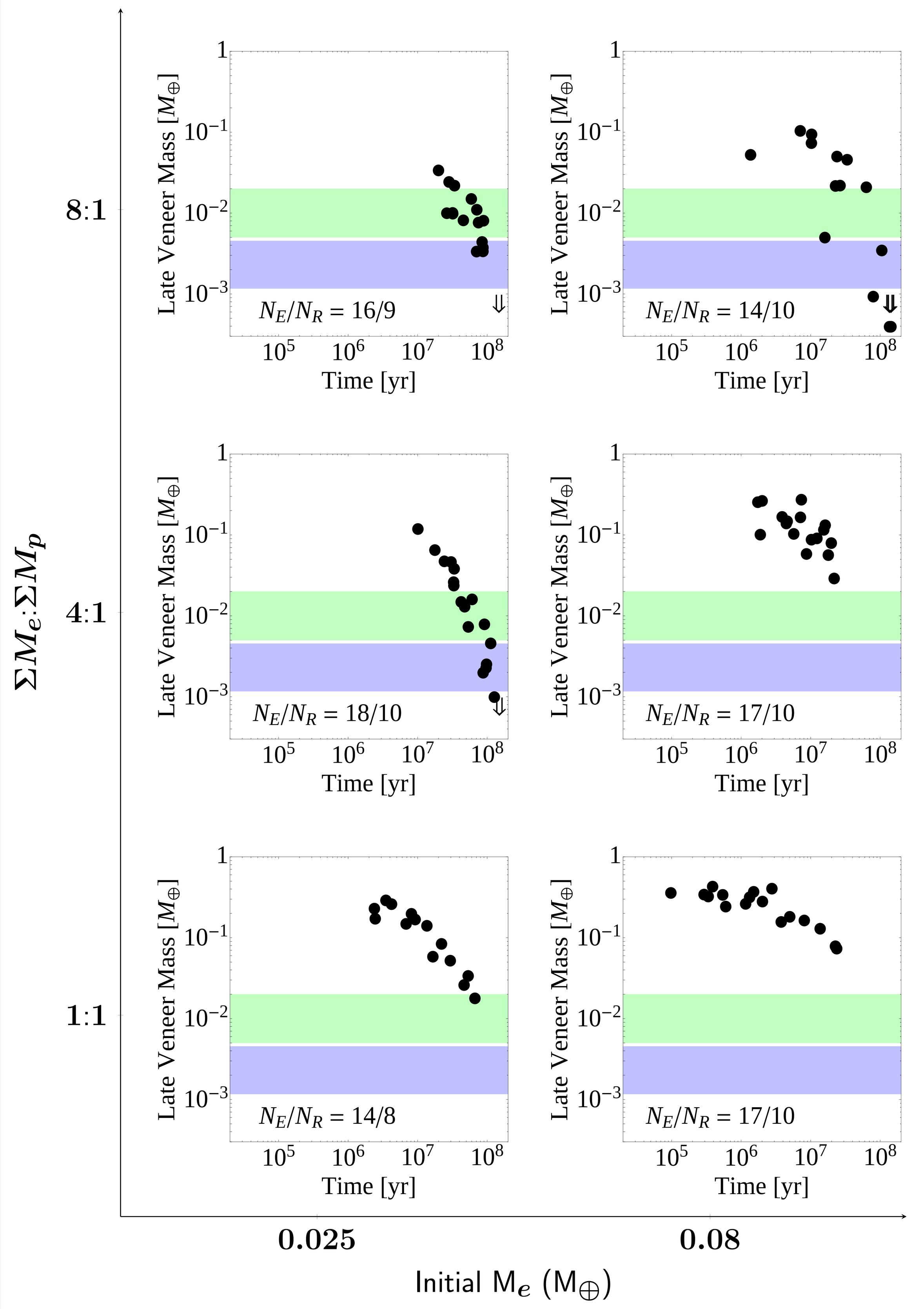
The mass and time of the last giant (embryo) impactor are shown for each model Earth as a black point. The colored regions are explained below.



- Horizontal bands are suggested projectile masses, from top to bottom: Canup (2012), Canup (2008) and Cuk & Stewart (2012).
- Vertical bands are suggested impact times, from left to right: the combined predictions of Jacobsen (2005) and Kleine et al. (2005) and the prediction of Touboul et al. (2007).
- More consistent masses and times at larger $\Sigma M_e{:}\Sigma M_p$ and lower initial M_e, also true for late veneer mass

Late Veneer Mass (accretion after last giant impact)

The mass of the late veneer on each Earth analog is shown against the time of the last giant (embryo) impact as a black point. The colored regions are explained below. For reference, N_E/N_R is the number of Earth analogs over the number of runs in that suite.



- Arrows indicate late veneer masses below 10^{-3} $M_\oplus$, often only a single or zero post giant impact planetesimals.
- Green and blue horizontal bands highlight late veneer masses argued in Chou (1978) and Dauphas & Marty (2002), respectively.
- Clear correlation between late veneer mass and the time of the last giant impact. **This argues for a late moon-forming event**

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