Formation of Close-in Super-Earths by Giant Impacts

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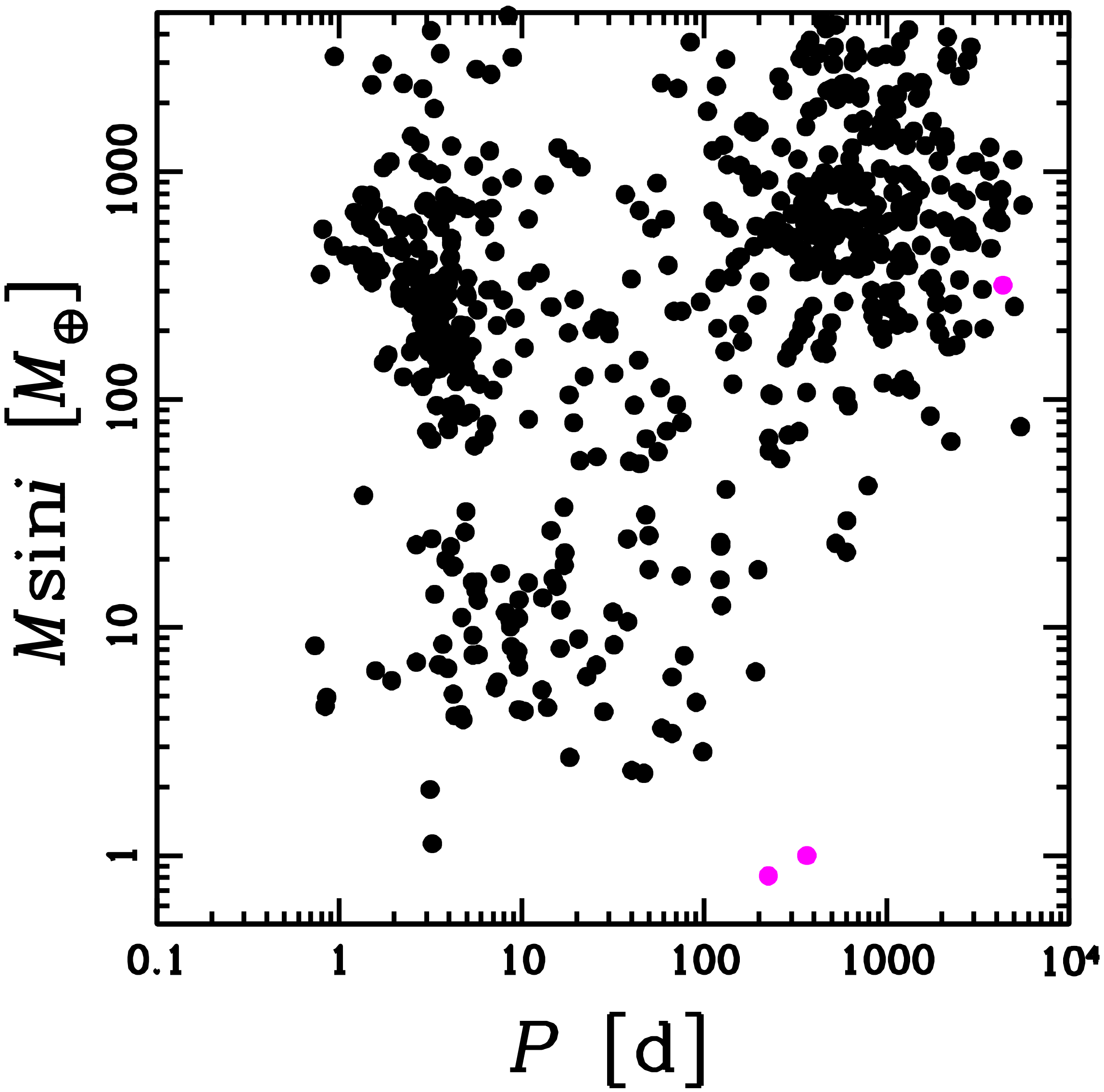
Exoplanets



Close-in Super-Earths: $P \lesssim 100\,\mathrm{d}$, $M \lesssim 30 M_\oplus$

Close-in Super-Earths

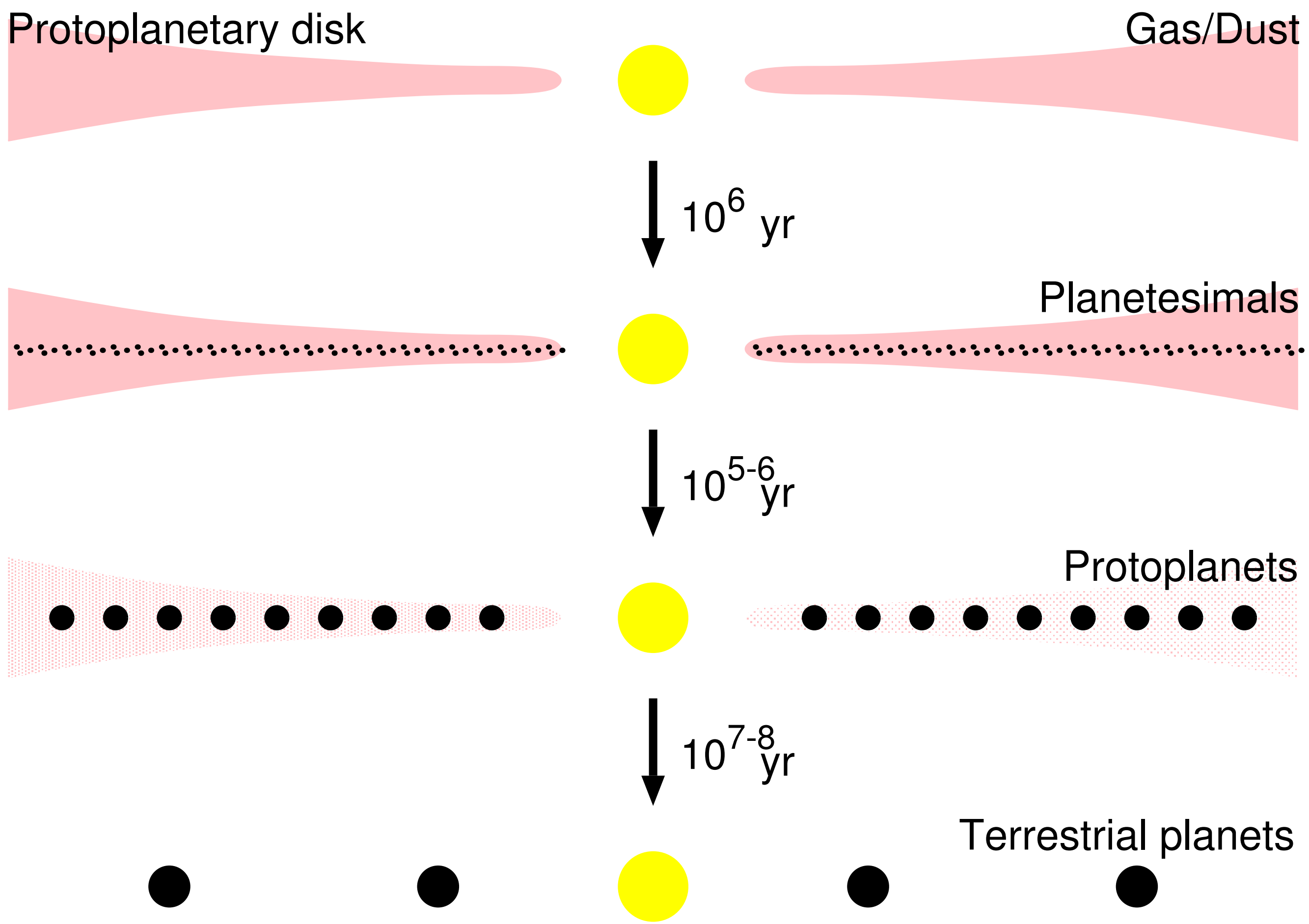
Definition

- $P \lesssim 100\,\mathrm{d}$ ($a \lesssim 0.4\,\mathrm{AU}$ for $M_* = M_\odot$)
- $M \lesssim 30 M_\oplus$

Properties

- $\gtrsim$ 50 % stars independent of metallicity
- $\simeq$ 70 % in multiple systems
- $M/M_* \sim 10^{-5}$
- $M_1/M_{\mathrm{tot}} \simeq 0.2$-$0.4$ (0.5)
- random P with slight excess around 3:2 and 2:1 MMRs
- smaller e and i ($e \lesssim 0.2$, $i \lesssim 0.05$) (~ 0.01-0.1)
- orbital separations $b \simeq 20$-$30 r_{\mathrm{H}}$ ($43 r_{\mathrm{H}}$)
  (solar system terrestrial planets)

The Standard Formation Scenario



Act 1 Dust to planetesimals (gravitational instability/binary coagulation)

Act 2 Planetesimals to protoplanets (runaway-oligarchic growth)

Act 3 Protoplanets to terrestrial planets (giant impacts)

Close-in SE Formation Scenarios

In-Situ Accretion

- Extension of the standard scenario to inner heavy disks

  (e.g., Raymond+ 2008; Montgomery & Laughlin 2009; Hansen & Murray 2012; Chiang & Laughlin 2013)

Accretion and Migration

- Formation farther out followed by inward migration due to gas

  (e.g., Lopez+ 2011; Kley & Nelson 2012; Rein 2012)

Migration and Accretion

- Inward migration in gas followed by giant impacts after gas dispersal

  (e.g., Terquem & Papaloizou 2007; Kennedy & Kenyon 2008; Ogihara & Ida 2009; Ida & Lin 2010)

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Close-in Giant Impacts? $\leftarrow$ *N*-Body Simulation

N-Body Simulation

Model

- planet: uniform sphere
- disk: gas-free
- collision: perfect accretion

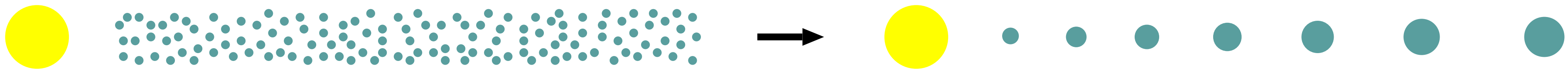
Integration Method

- Modified Hermite integrator for planetary dynamics (Kokubo & Makino 2004)
- Phantom-GRAPE (Nitadori+ 2006)
- A dedicated Opteron cluster “Terrestrial Planet Former”

Initial Conditions

- Protoplanets formed by oligarchic growth

Oligarchic Growth Model



planetesimals protoplanets

Planetesimal Disk Model

$$\Sigma_{\rm solid} = \Sigma_1 \left(\frac{a}{1\,{\rm AU}}\right)^{-\alpha}\ {\rm gcm}^{-2}$$

standard disk: $\Sigma_1 \simeq 10$, $\alpha = 3/2$

Assumptions

- orbital separation $b \propto$ Hill radius: $r_{\rm H} = \left(\frac{2M}{3M_\odot}\right)^{1/3} a$
- no radial migration, 100% accretion efficiency

Isolation Mass of Protoplanets

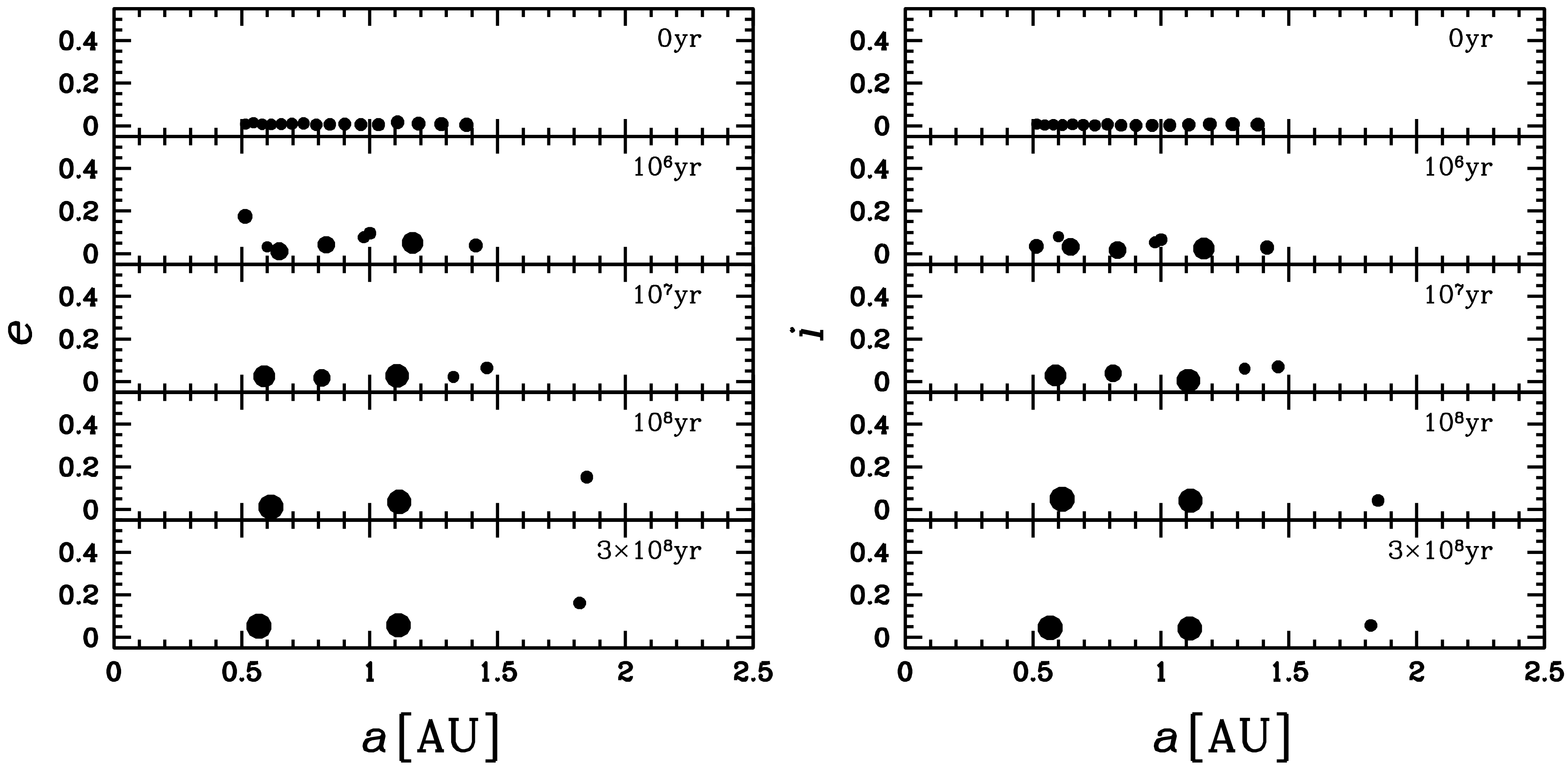
$$M_{\rm iso} \simeq 0.16 \left(\frac{\tilde{b}}{10}\right)^{3/2} \left(\frac{\Sigma_1}{10}\right)^{3/2} \left(\frac{a}{1\,{\rm AU}}\right)^{(3/2)(2-\alpha)} M_\oplus$$

$\tilde{b} = b/r_{\rm H}$

(Kokubo & Ida 2002)

An Example Run for $a \sim 1\,\mathrm{AU}$

$\Sigma_1 = 10$, $\alpha = 3/2$, $\tilde{b} = 10$, $r_{\rm in} = 0.5\,\mathrm{AU}$, $r_{\rm out} = 1.5\,\mathrm{AU}$ ($n = 16$, $M_{\rm tot} = 2.3 M_\oplus$)



$$n = 3, n_M(M > M_\oplus/2) = 2$$

$$M_1 = 1.1 M_\oplus\ (a_1 = 0.59\,\mathrm{AU}, e_1 = 0.05, i_1 = 0.05)$$

$$M_2 = 1.0 M_\oplus\ (a_2 = 1.12\,\mathrm{AU}, e_2 = 0.04, i_2 = 0.04)$$

Giant Impacts for $a \sim 1\,\mathrm{AU}$

Planets for the Standard Disk

- disk: $\Sigma_1 = 10$, $\alpha = 3/2$, $b = 10 r_{\mathrm{H}}$, $r_{\mathrm{in}} = 0.5\,\mathrm{AU}$, $r_{\mathrm{out}} = 1.5\,\mathrm{AU}$
- planets: 2 Earth-sized planets with 1 or 2 leftover protoplanets
  - mass: $\langle M_1/M_{\mathrm{tot}} \rangle \simeq 0.56$
  - orbit: $\langle \bar{b} \rangle \simeq 48 r_{\mathrm{H}}$, $e, i \simeq 0.1$ (dynamically hot loose system)

Mass Scaling Laws

- mass: $\langle M_1 \rangle, \langle M_2 \rangle \propto M_{\mathrm{tot}}$, $\langle M_2/M_1 \rangle \simeq 0.6$

(Kokubo+ 2006; Kokubo & Ida in prep.)

Close-in Giant Impacts

Key Parameter

- Larger physical to Hill radius ratio: $r_\mathrm{p}/r_\mathrm{H} \propto a^{-1}$ (close scattering is inhibited)

Large $r_\mathrm{p}/r_\mathrm{H}$ Effects

- No close scattering among protoplanets $\longrightarrow$
- smaller e, less mobility $\longrightarrow$
- local accretion $\longrightarrow$
- dynamically cold compact multiple system?

Hill Radius

Radius of the potential well of an orbiting body

$$r_\mathrm{H} = \left(\frac{M}{3M_*}\right)^{1/3} a$$

M_* : central body mass, M : orbiting body mass, a : semimajor axis

Initial Conditions

Planetesimal Disks

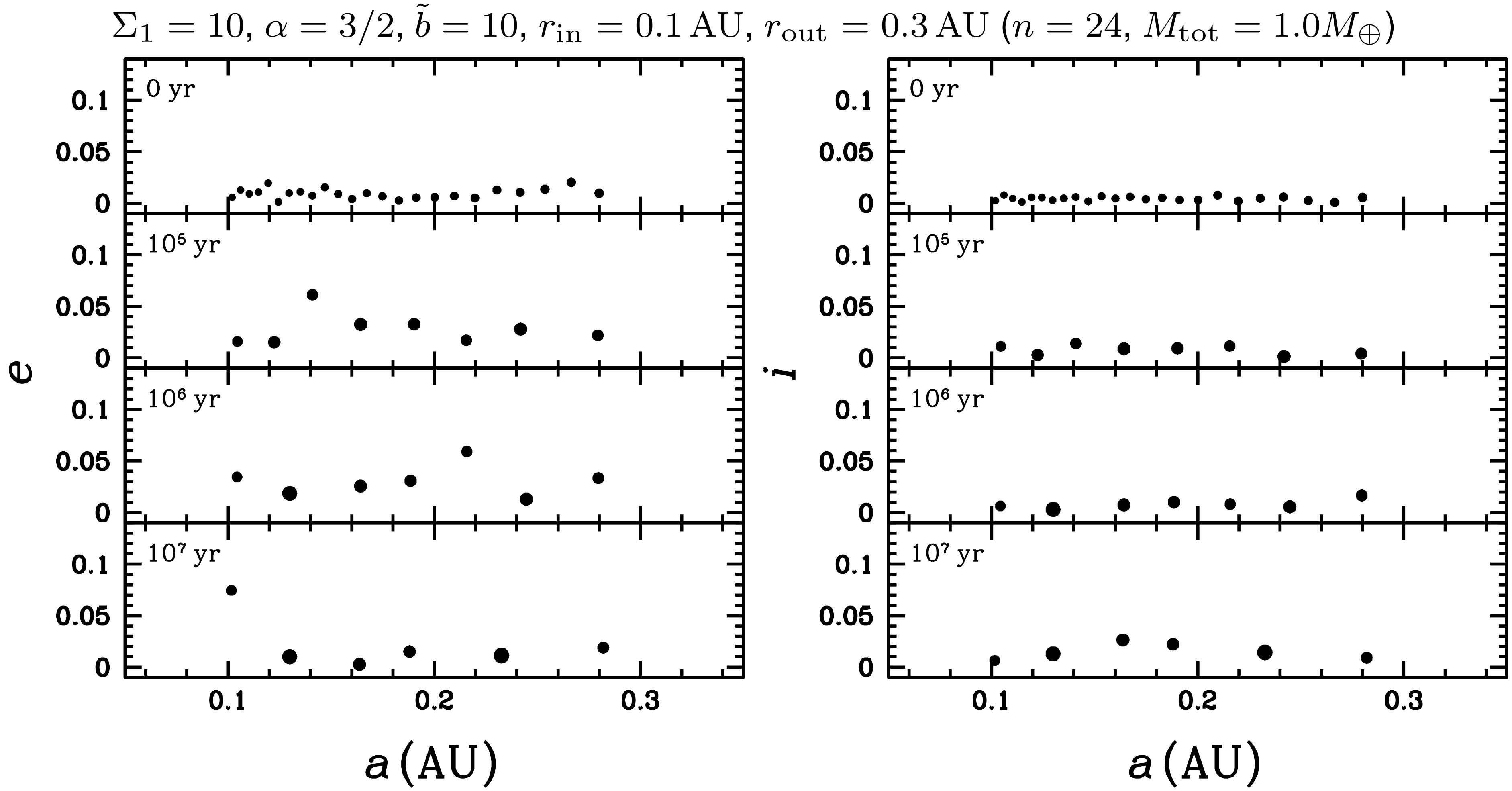
- surface density at 1 AU: $\Sigma_1 = 10, 30, 100$
- radial profile: $\alpha = 3/2$
- inner cutoff: $r_{\text{in}} = 0.5 \rightarrow 0.1\,\text{AU}$
- outer cutoff: $r_{\text{out}} = 1.5 \rightarrow 0.3\,\text{AU}$ (1/5 downsizing)

$$\Sigma = \Sigma_1 \left(\frac{a}{1\text{AU}}\right)^{-\alpha}, \; M_{\text{tot}} = \int_{r_{\text{in}}}^{r_{\text{out}}} \Sigma 2\pi a \text{d}a$$

Protoplanets

- orbital separation: $\tilde{b} = 10$
- eccentricity and inclination:
  $\langle e^2 \rangle^{1/2} = 2\langle i^2 \rangle^{1/2} = 0.01(\Sigma_1/10)^{1/2}$
- material density: $\rho = 3.0\,\text{gcm}^{-3}$

$\Sigma_1 = 10$ Disk – An Example Run

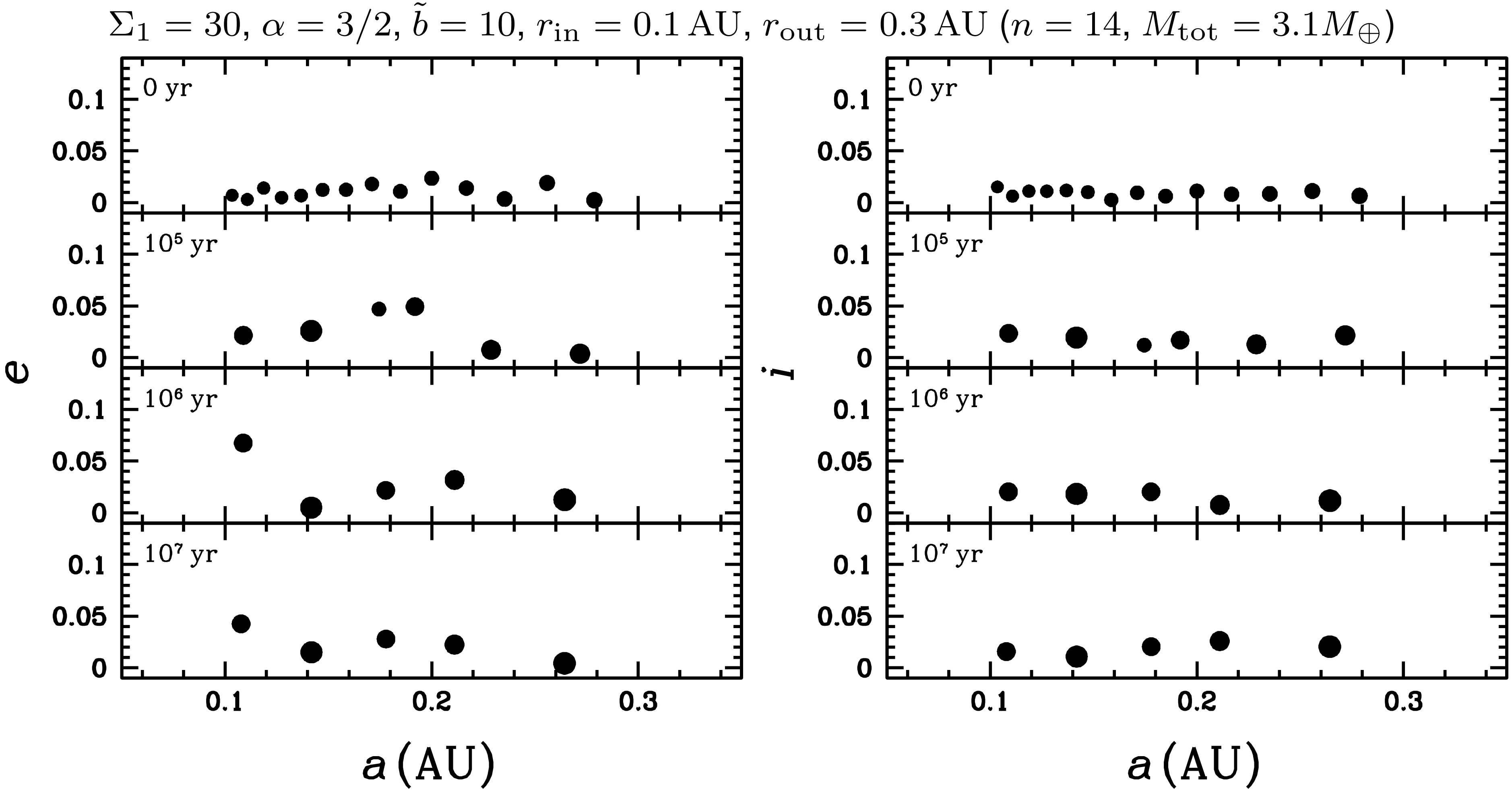


$n = 6$

$M_1 = 0.27 M_\oplus$ ($a_1 = 0.23\,$AU$, e_1 = 0.01, i_1 = 0.01$)

$M_2 = 0.24 M_\oplus$ ($a_2 = 0.13\,$AU$, e_2 = 0.01, i_2 = 0.02$)

$\Sigma_1 = 30$ Disk – An Example Run



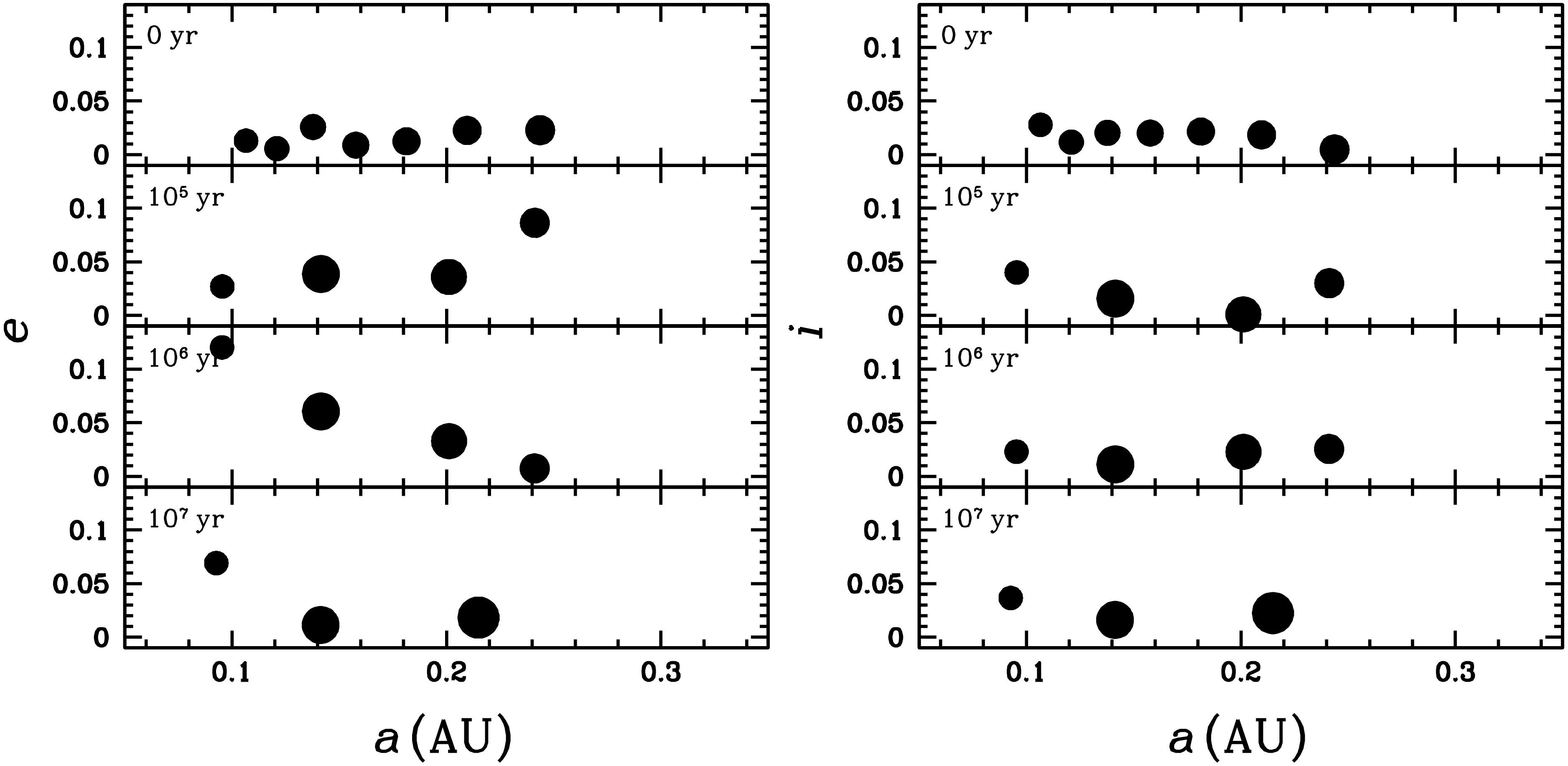
$n = 5$

$M_1 = 0.84 M_\oplus$ ($a_1 = 0.26\,\mathrm{AU}, e_1 = 0.00, i_1 = 0.02$)

$M_2 = 0.78 M_\oplus$ ($a_2 = 0.14\,\mathrm{AU}, e_2 = 0.02, i_2 = 0.01$)

$\Sigma_1 = 100$ Disk – An Example Run

$\Sigma_1 = 100$, $\alpha = 3/2$, $\tilde{b} = 10$, $r_{\rm in} = 0.1\,{\rm AU}$, $r_{\rm out} = 0.3\,{\rm AU}$ ($n = 7$, $M_{\rm tot} = 9.3 M_\oplus$)



$n = 3$

$M_1 = 4.8 M_\oplus$ ($a_1 = 0.21\,{\rm AU}, e_1 = 0.02, i_1 = 0.02$)

$M_2 = 3.5 M_\oplus$ ($a_2 = 0.14\,{\rm AU}, e_2 = 0.01, i_2 = 0.02$)

Results–Mass

$\alpha = 3/2$, $b_{\rm ini} = 10 r_{\rm H}$, $r_{\rm in} = 0.1\,{\rm AU}$, $r_{\rm out} = 0.3\,{\rm AU}$, $t = 10^7\,{\rm yr}$

model	Σ_1	$n_{\rm ini}$	$M_{\rm tot}\ (M_\oplus)$	$\langle n_{\rm fin}/a \rangle\ ({\rm AU}^{-1})$	$\langle M_1/M_{\rm tot} \rangle$	$\langle \sigma_M/\bar{M} \rangle$
1	10	24	1.0	31.5	0.24	0.31
2	30	14	3.1	23.0	0.33	0.32
3	100	7	9.3	17.5	0.42	0.34

$\alpha = 3/2$, $b_{\rm ini} = 10 r_{\rm H}$, $r_{\rm in} = 0.5\,{\rm AU}$, $r_{\rm out} = 1.5\,{\rm AU}$, $t = 2 \times 10^8\,{\rm yr}$

model	Σ_1	$n_{\rm ini}$	$M_{\rm tot}\ (M_\oplus)$	$\langle n_{\rm fin}/a \rangle\ ({\rm AU}^{-1})$	$\langle M_1/M_{\rm tot} \rangle$	$\langle \sigma_M/\bar{M} \rangle$
1’	10	16	2.3	3.4	0.56	0.61

Fixed Σ_1: $r\downarrow \Longrightarrow \langle n_{\rm fin}/a \rangle\uparrow$, $\langle M_1/M_{\rm tot} \rangle\downarrow$, $\langle \sigma_M/\bar{M} \rangle\downarrow$

Fiexd: r: $\Sigma_1\uparrow \Longrightarrow \langle n_{\rm fin}/a \rangle\downarrow$, $\langle M_1/M_{\rm tot} \rangle\uparrow$

Close-in → Compact similar-mass system

Results–Orbit

$\alpha = 3/2$, $b_{\rm ini} = 10 r_{\rm H}$, $r_{\rm in} = 0.1\,{\rm AU}$, $r_{\rm out} = 0.3\,{\rm AU}$, $t = 10^7\,{\rm yr}$

model	Σ_1	$n_{\rm ini}$	$M_{\rm tot}\ (M_\oplus)$	$\langle \bar{b} \rangle\ (r_{\rm H})$	$\langle e_1 \rangle$	$\langle i_1 \rangle$
1	10	24	1.0	26	0.02	0.01
2	30	14	3.1	23	0.02	0.02
3	100	7	9.3	19	0.04	0.02

$\alpha = 3/2$, $b_{\rm ini} = 10 r_{\rm H}$, $a_{\rm in} = 0.5\,{\rm AU}$, $a_{\rm out} = 1.5\,{\rm AU}$, $t = 2 \times 10^8\,{\rm yr}$

model	Σ_1	$n_{\rm ini}$	$M_{\rm tot}\ (M_\oplus)$	$\langle \bar{b} \rangle\ (r_{\rm H})$	$\langle e_1 \rangle$	$\langle i_1 \rangle$
1'	10	16	2.3	48	0.12	0.06

Fixed Σ_1: $r\downarrow \Longrightarrow \langle \bar{b} \rangle\downarrow, \langle e_1 \rangle\downarrow, \langle i_1 \rangle\downarrow$

Fiexd r: $\Sigma_1\uparrow \Longrightarrow \langle \bar{b} \rangle\downarrow, \langle e_1 \rangle\uparrow, \langle i_1 \rangle\uparrow$

Close-in $\rightarrow$ Cold compact system

Summary

Close-in Giant Impacts

- large $r_\mathrm{p}/r_\mathrm{H} \rightarrow$ cold compact multiple system
- mass: comparable, $M_1/M_\mathrm{tot} \simeq 0.2$-$0.4$
- orbit: $b \simeq 20$-$30 r_\mathrm{H}$, $e, i \lesssim 0.04$, non-resonant

Discussion

- Many compact close-in Mars systems?
- Why no planets inside Mercury's orbit in the solar system?

Future Works

- More disk models to generalize the results
- Long-term stability
- Comparison with observation