Orbital Architecture of Planetary Systems Formed by Giant Impacts

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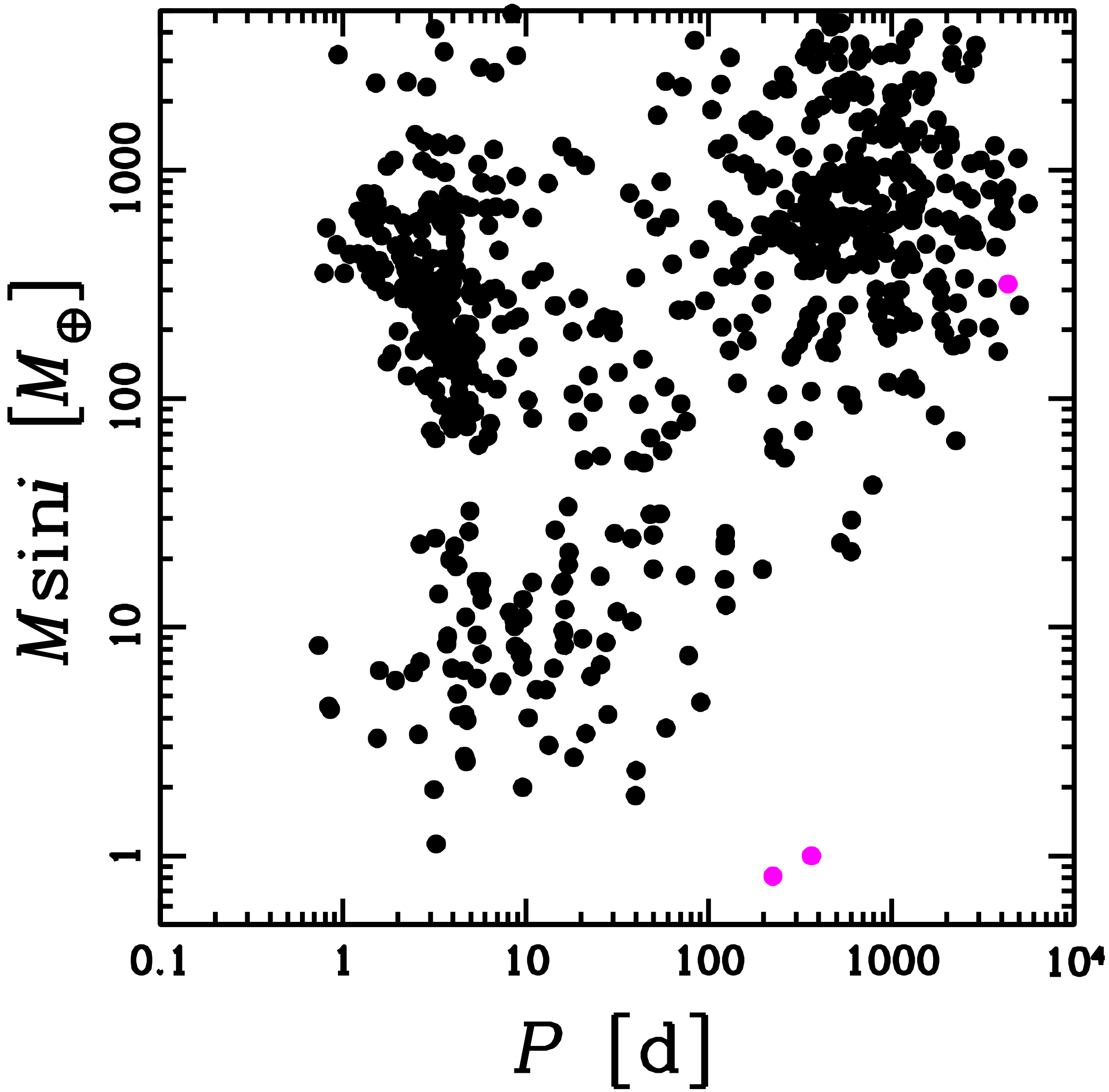
Exoplanets



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

Close-in Terrestrial Planets

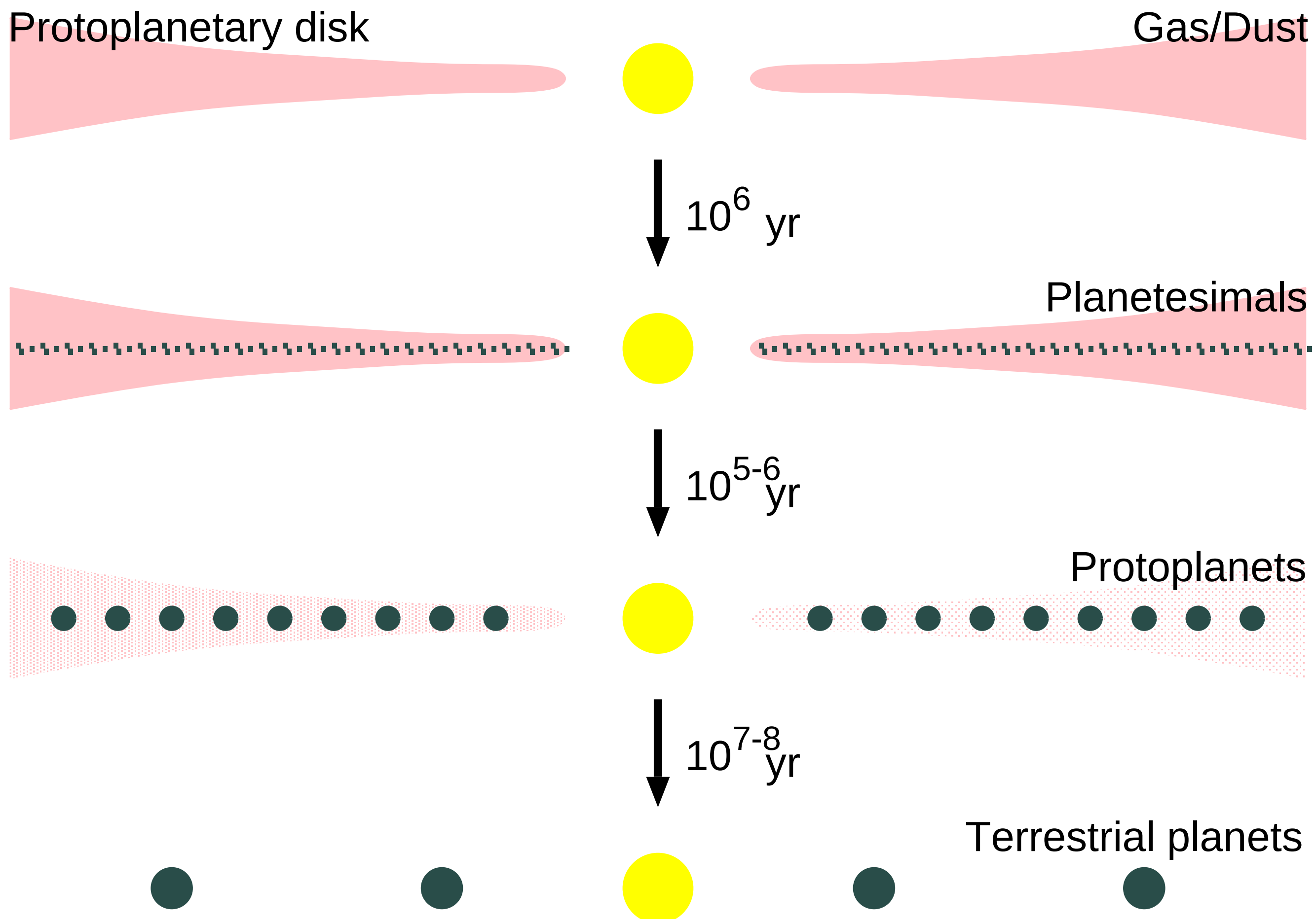
Definition

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

Properties

- $\gtrsim$ 50 % stars independent of metallicity
- $\simeq$ 70 % in multiple systems
- $M_1/M_{\mathrm{tot}} \simeq 0.3$-$0.4$ (0.5)
- random P with slight excess around 3:2 and 2:1 MMRs
- small e and i ($e \lesssim 0.2$, $i \lesssim 0.05$) (~ 0.01-0.1)
- orbital separation $b \simeq 15$-$30 r_{\mathrm{H}}$ (r_{H}: the Hill radius) ($43 r_{\mathrm{H}}$) (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 TP 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; Lee & Chiang 2016; Dawson+ 2016)

Accretion and then Migration

- Formation far out followed by inward migration due to gas
  (e.g., Lopez+ 2011; Kley & Nelson 2012; Rein 2012)

Migration and then Accretion

- Inward migration due to gas followed by giant impacts after gas dispersal
  (e.g., Terquem & Papaloizou 2007; Kennedy & Kenyon 2008; Ogihara & Ida 2009; Ida & Lin 2010; Ogihara+ 2015)

Close-in Giant Impacts?

Goal

To clarify the final stage of terrestrial planet formation

Protoplanet System $\Longrightarrow$ Terrestrial Planet System

- Number?
- Mass?

- Orbit?
- Spin?

(EK+ 2006, EK & Ida 2007, EK & Genda 2010, Genda+ 2012, Genda+ 2015, Matsumoto & EK in prep., Oshino+ in prep., ...)

Strategy

N-body simulation of terrestrial planet formation from protoplanets

- systematically different initial conditions (not only solar system formation)
- statistical analysis with many runs

Self-Gravitating Particle Disk

Disk Properties

- many-body (particulate) system
- rotation
- self-gravity
- dissipation (collisions and accretion)

Planet Formation as Disk Evolution

- evolution of a dissipative self-gravitating particulate disk
- velocity and spatial evolution $\leftrightarrow$ mass evolution

Final Configuration?

N-Body Simulation

Model

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

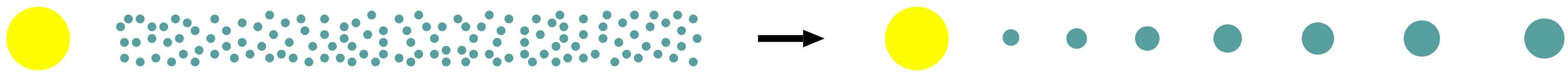
Integration Method

- Modified Hermite integrator for planetary dynamics (EK & Makino 2004)
- Phantom-GRAPE (Nitadori+ 2006)

Initial Conditions

- Protoplanets formed by oligarchic growth (EK & Ida 2002)

Oligarchic Growth Model



planetesimals protoplanets

Planetesimal Disk Model

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

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

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

(EK & Ida 2002)

Initial Conditions

Planetesimal Disks

- surface density at 1 AU: $\Sigma_1 = 10, 30, 100$
- radial profile: $\alpha = 3/2, 2, 5/2$
- radial range: $r = 0.05$-$0.15, 0.1$-0.3, 0.2-0.6, 0.5-$1.5\,\mathrm{AU}$

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

Protoplanets

- orbital separation: $b = 5, 10, 15 r_{\mathrm{H}}$ (r_{H}: the Hill radius)
- eccentricity and inclination: $\langle e^2 \rangle^{1/2} = 2\langle i^2 \rangle^{1/2} = 0.0025$-$0.16$
- material density: $\rho = 3.0\,\mathrm{g cm}^{-3}$

System Parameters

Mass Distribution

- most massive: $M_1/M_{\rm tot}$ (0.51)
- dispersion: $\sigma_M/\bar{M}$ (0.85)

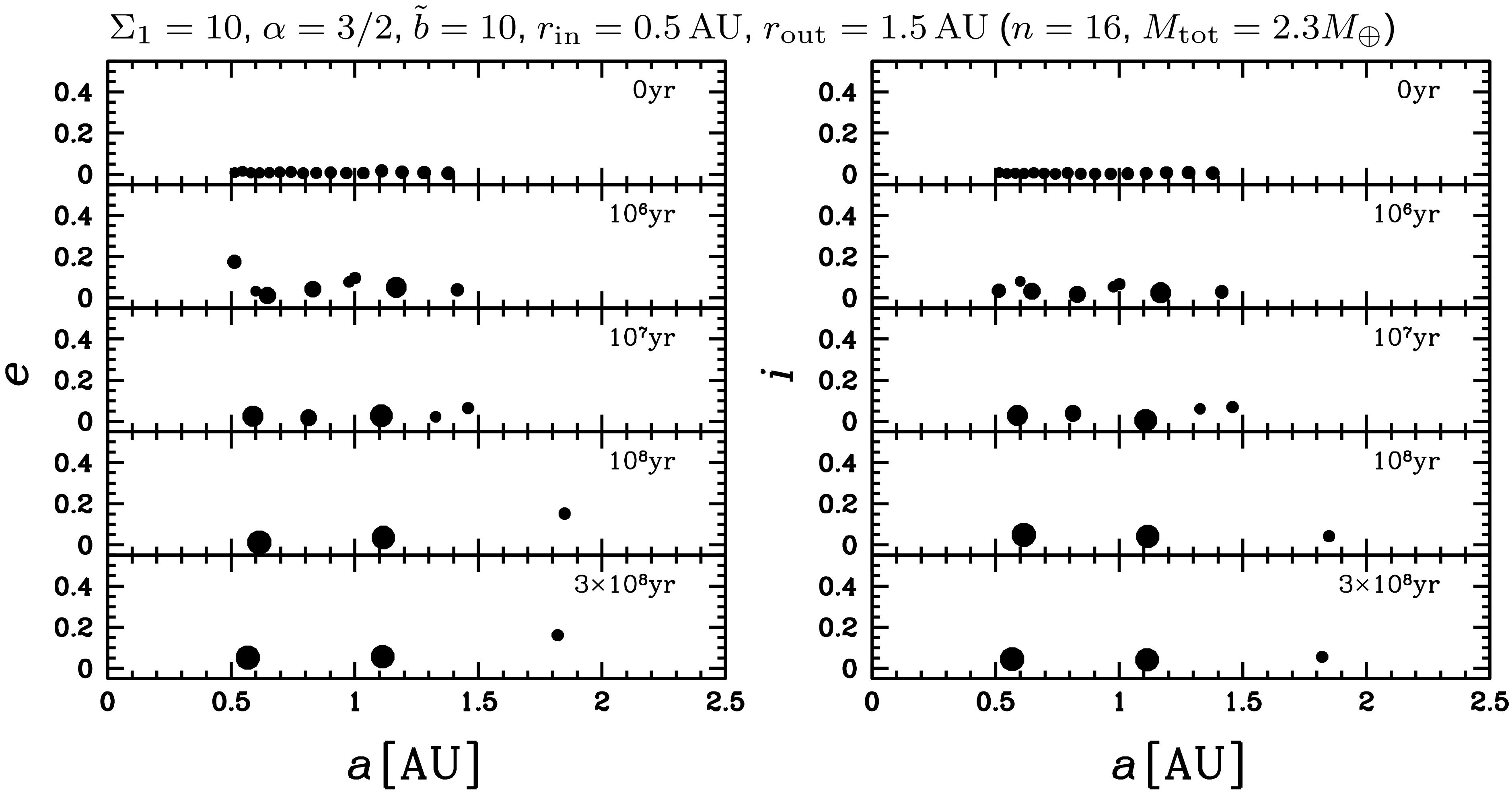
Orbital Structure

- mass-weighted orbital elements: $\langle a \rangle_M$, $\langle e \rangle_M$, $\langle i \rangle_M$ ($0.90\,\mathrm{AU}$, 0.022, 0.034)
- mean orbital separation: $\tilde{b} = b/r_{\rm H}$ (43)
- mean epicycle amplitude: $\tilde{e} = ea/r_{\rm H}$ (10)
- angular momentum deficit (AMD): (0.0018)

$$D = \frac{\sum_j M_j \sqrt{a_j}\left(1 - \sqrt{1 - e_j^2}\cos i_j\right)}{\sum_j M_j \sqrt{a_j}} \simeq \frac{\sum_j M_j (e_j^2 + i_j^2)/2}{\sum_j M_j}$$ (Hill's approximation)

(solar system terrestrial planets)

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



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

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

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

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

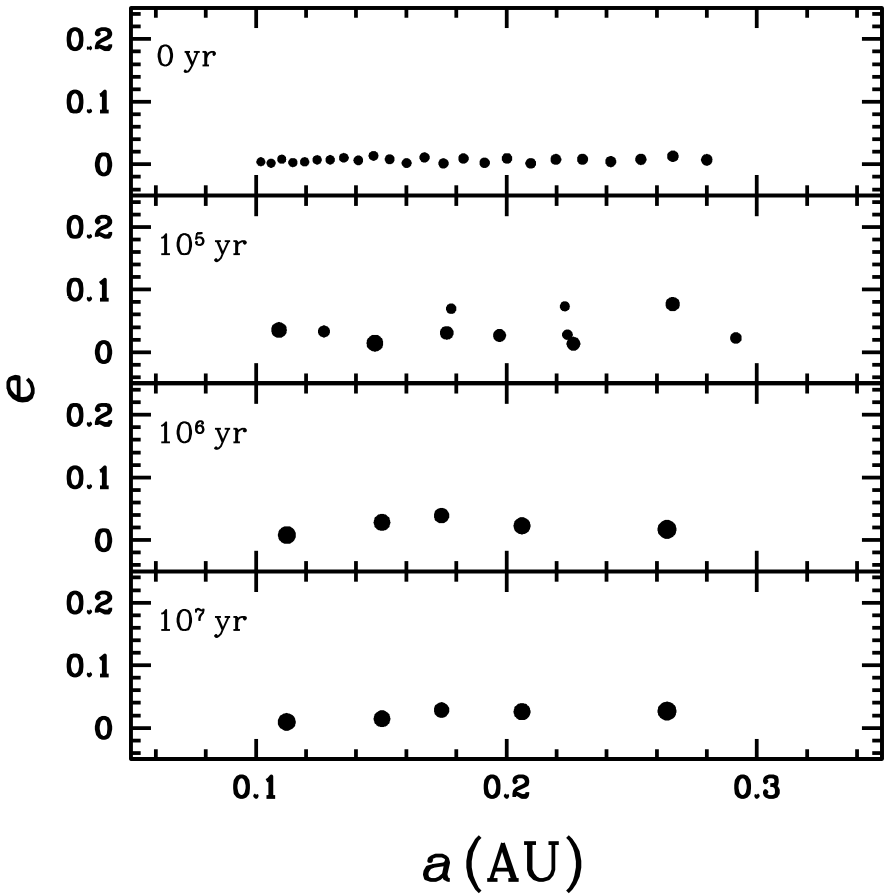
- mass: $\langle M_1 \rangle, \langle M_2 \rangle \propto M_{\mathrm{tot}}$, $\langle M_2/M_1 \rangle \simeq 0.6$

(EK+ 2006; EK & Ida 2007; EK & Genda 2010; EK+ in prep.)

System Radius Dependence (1)

$$\Sigma_1 = 10,\ \alpha = 3/2,\ b = 10 r_{\rm H}$$

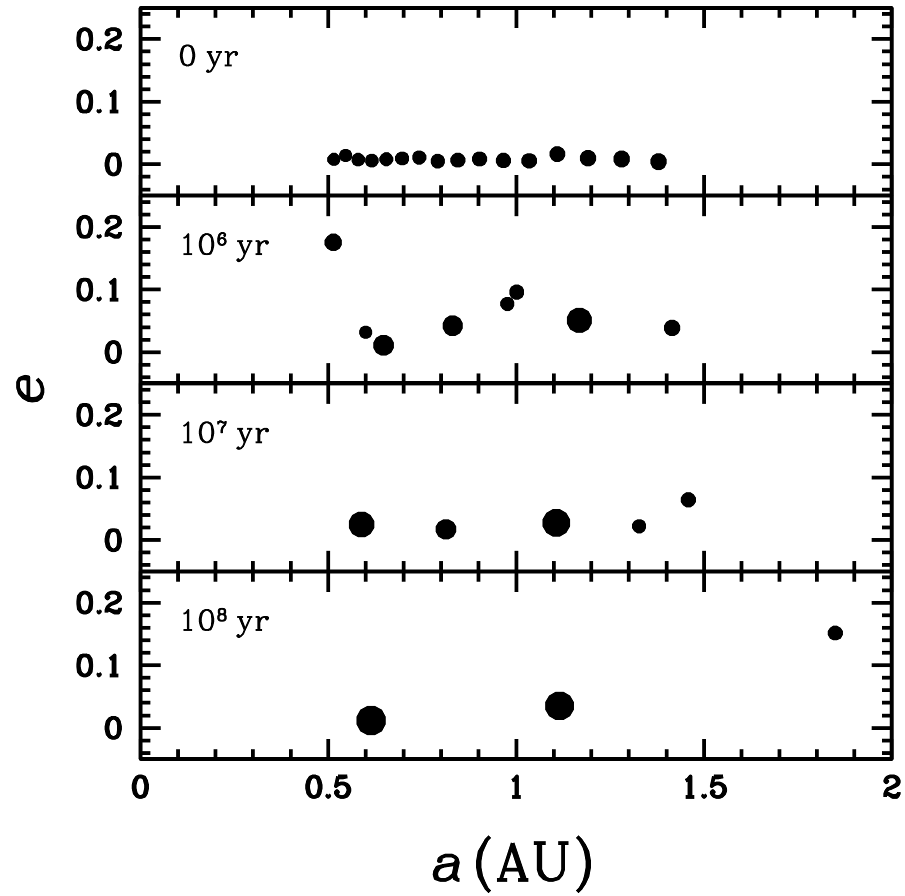
$r = 0.1\text{-}0.3\ \mathrm{AU}$



$N:\ 24 \rightarrow 5$

compact, dynamically cold

$r = 0.5\text{-}1.5\ \mathrm{AU}$



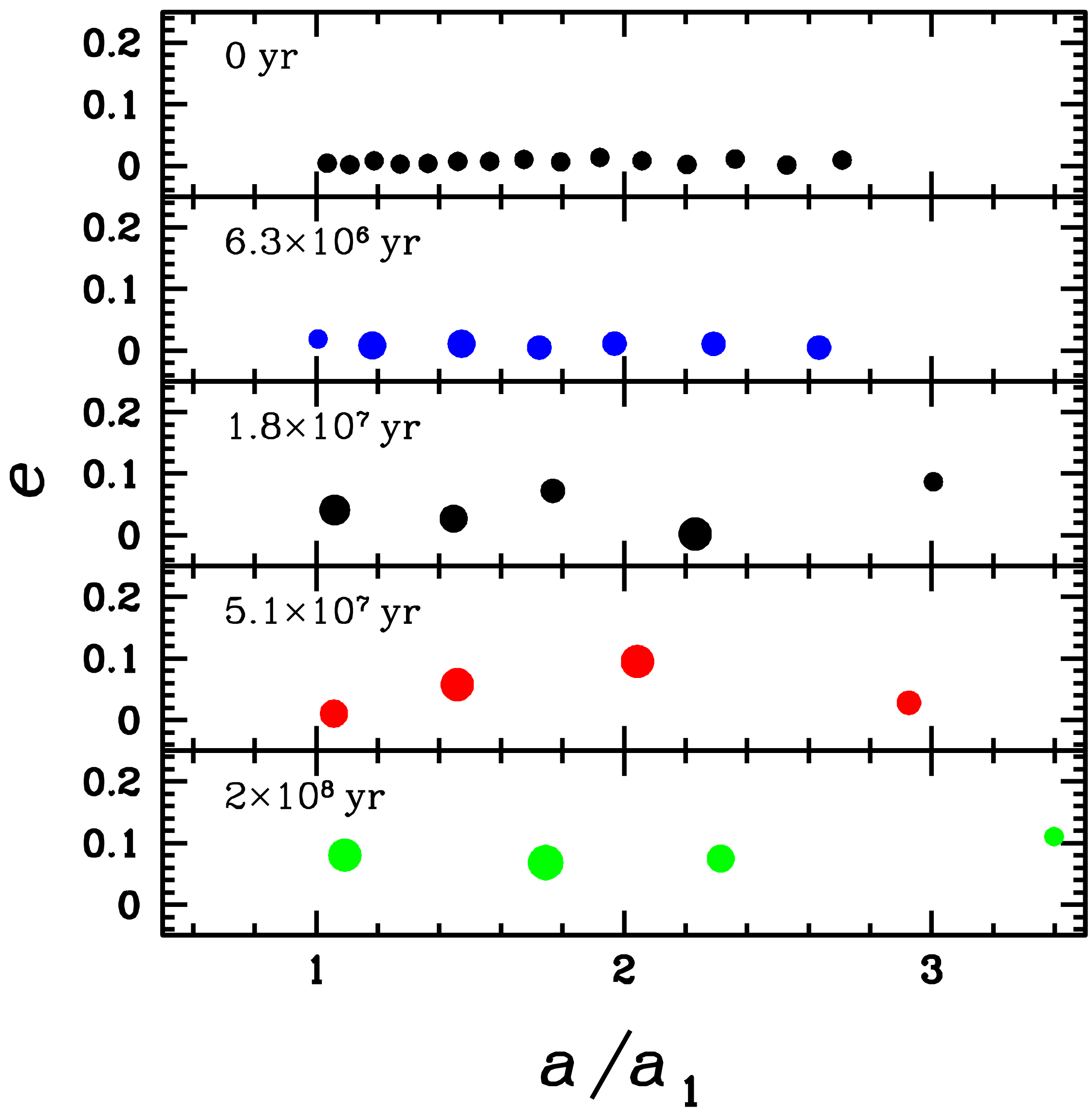
$N:\ 16 \rightarrow 3$

sparse, dynamically hot

System Radius Dependence (2)

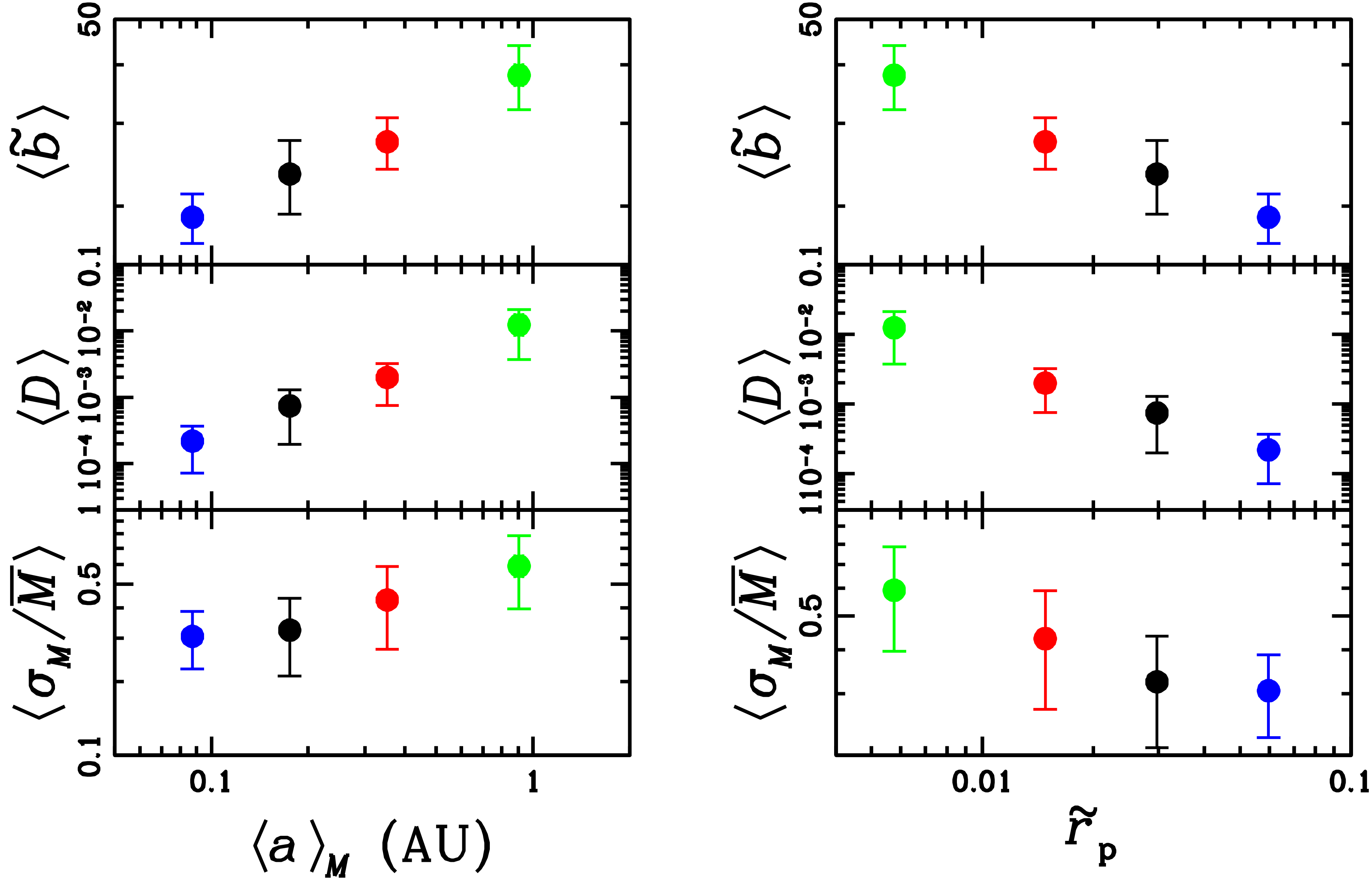
$\Sigma_1 = 10$, $\alpha = 2$, $b = 10r_{\rm H}$, $\langle e^2\rangle^{1/2} = 0.01$, $r =$ 0.05-0.15, 0.1-0.3, 0.2-0.6, 0.5-1.5 AU

$t = 2 \times 10^8 t_{\rm K}$



System Radius Dependence (3)

$\Sigma_1 = 10$, $\alpha = 2$, $b = 10r_{\rm H}$, $\langle e^2\rangle^{1/2} = 0.01$, $r =$ 0.05-0.15, 0.1-0.3, 0.2-0.6, 0.5-1.5 AU



$$\mathrm{d}\log\langle\tilde{b}\rangle/\mathrm{d}\log\tilde{r}_{\rm p} \simeq -0.3$$

Close-in Giant Impacts

Key Parameter

- physical to Hill radius ratio: $\tilde{r}_\mathrm{p} = r_\mathrm{p}/r_\mathrm{H} = \left(\frac{9M_*}{4\pi\rho}\right)^{1/3}\left(\frac{1}{a}\right)$

Large $\tilde{r}_\mathrm{p}$ Effects

- relatively weak scattering and effective collisions $\rightarrow$
  smaller e, less mobility $\rightarrow$
  local accretion $\rightarrow$
  dynamically cold compact comparable-mass system

Hill Radius

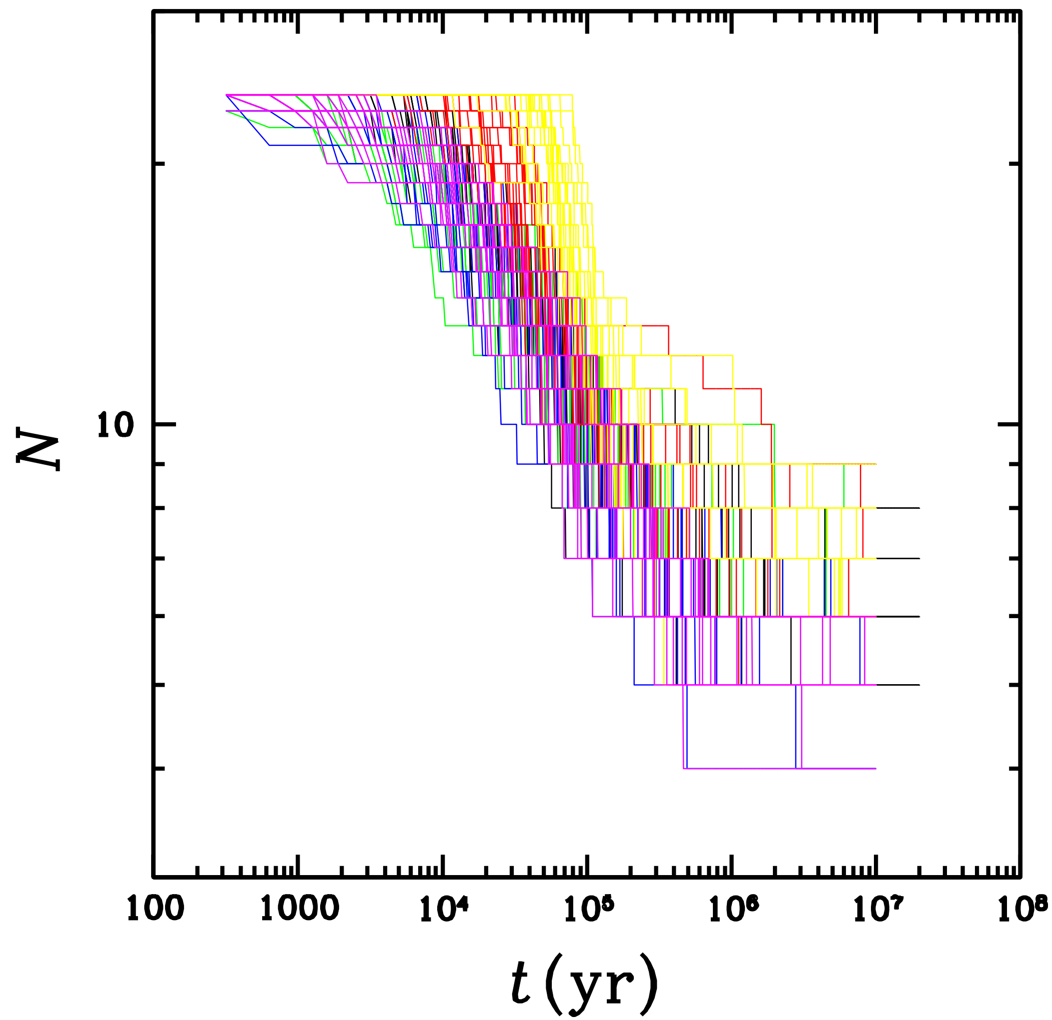
- radius of the potential well of an orbiting body

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

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

Accretionary Evolution

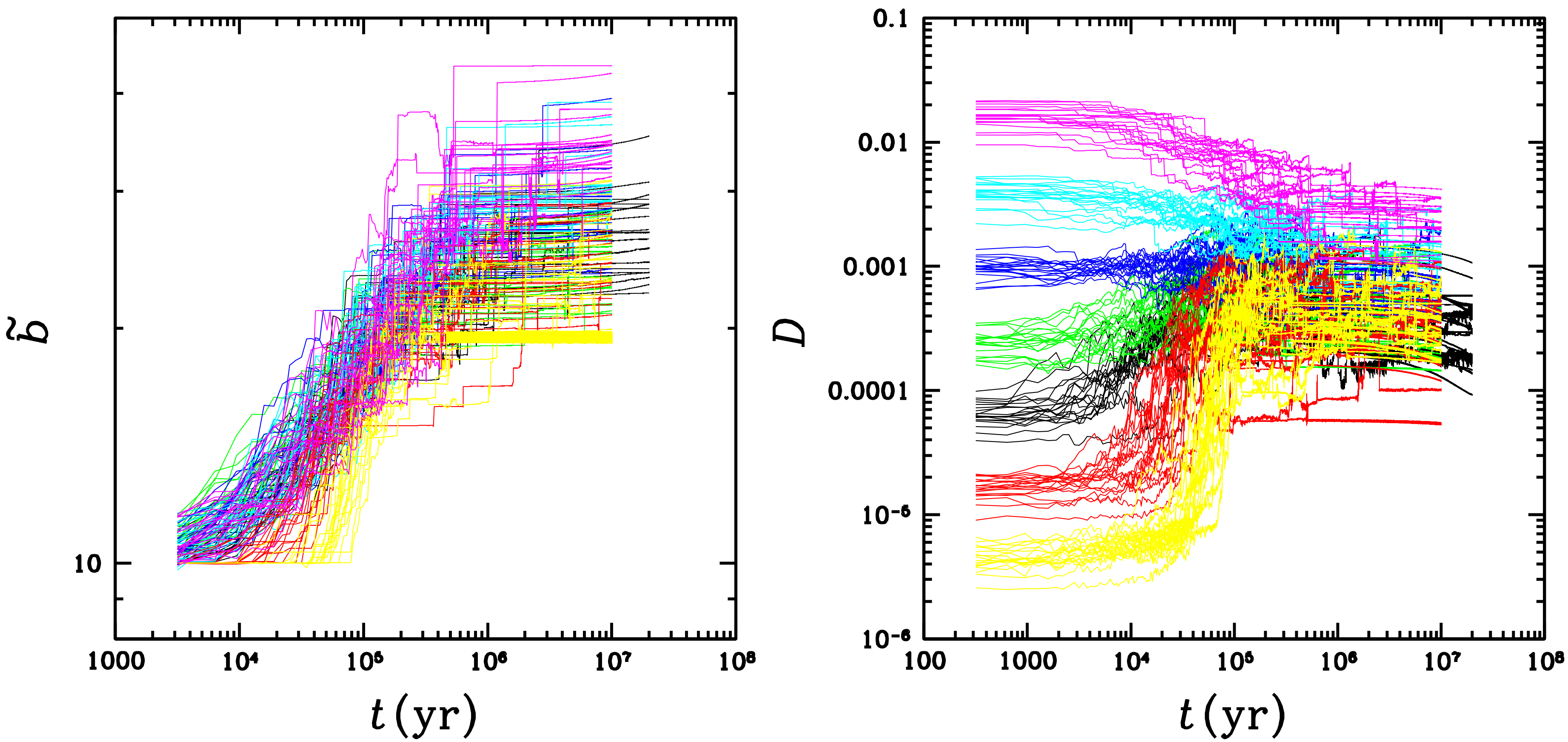
$\Sigma_1 = 10$, $\alpha = 3/2$, $r = 0.1$-$0.3\,\mathrm{AU}$, $b = 10 r_{\mathrm{H}}$, $\langle e^2 \rangle^{1/2} =$ 0.0025, 0.005, 0.01, 0.02, 0.04, 0.08, 0.16



N decreases with time by giant impacts

Orbital Evolution (1)

$\Sigma_1 = 10$, $\alpha = 3/2$, $r = 0.1\text{-}0.3\,\mathrm{AU}$, $b = 10r_\mathrm{H}$, $\langle e^2 \rangle^{1/2} =$ 0.0025, 0.005, 0.01, 0.02, 0.04, 0.08, 0.16



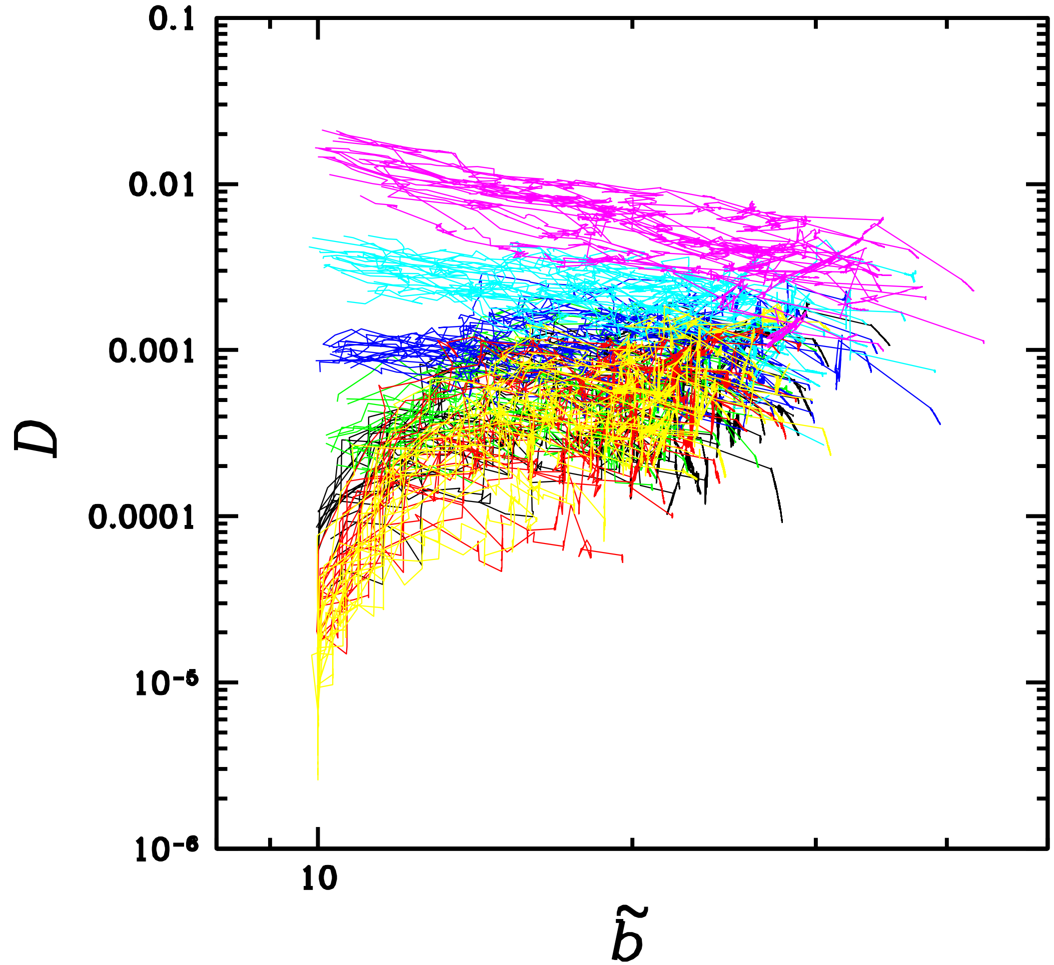
D converges on some range as $\tilde{b}$ increases

Gravitational Relaxation ($D \uparrow$) $\rightarrow$ Orbital Instability $\rightarrow$ Collisions ($\tilde{b} \uparrow$)

$\log t_\mathrm{inst} \simeq c_1 \tilde{b} + c_2$ (e.g., Chambers+ 1996, Yoshinaga, EK+ 1999)

Orbital Evolution (2)

$\Sigma_1 = 10$, $\alpha = 3/2$, $r = 0.1$-$0.3\,\mathrm{AU}$, $b = 10 r_{\mathrm{H}}$, $\langle e^2 \rangle^{1/2} =$ 0.0025, 0.005, 0.01, 0.02, 0.04, 0.08, 0.16

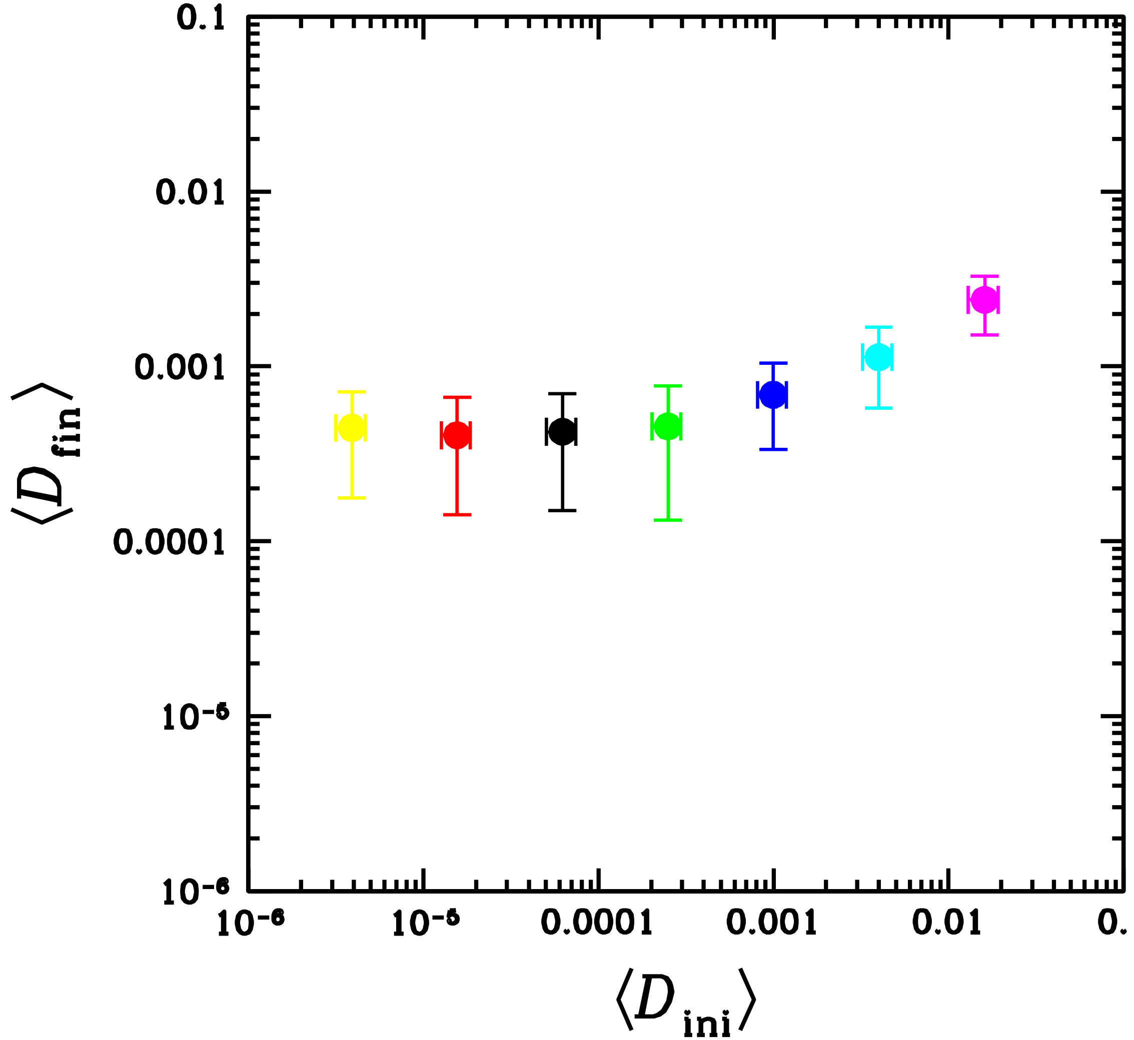


D converges on some range as $\tilde{b}$ increases

Gravitational Relaxation ($D \uparrow$) $\rightarrow$ Orbital Instability $\rightarrow$ Collisions ($\tilde{b} \uparrow$)

D_{ini}-Dependence

$\Sigma_1 = 10$, $\alpha = 3/2$, $r = 0.1$-$0.3\,\mathrm{AU}$, $b = 10 r_{\mathrm{H}}$, $\langle e^2 \rangle^{1/2} =$ 0.0025, 0.005, 0.01, 0.02, 0.04, 0.08, 0.16

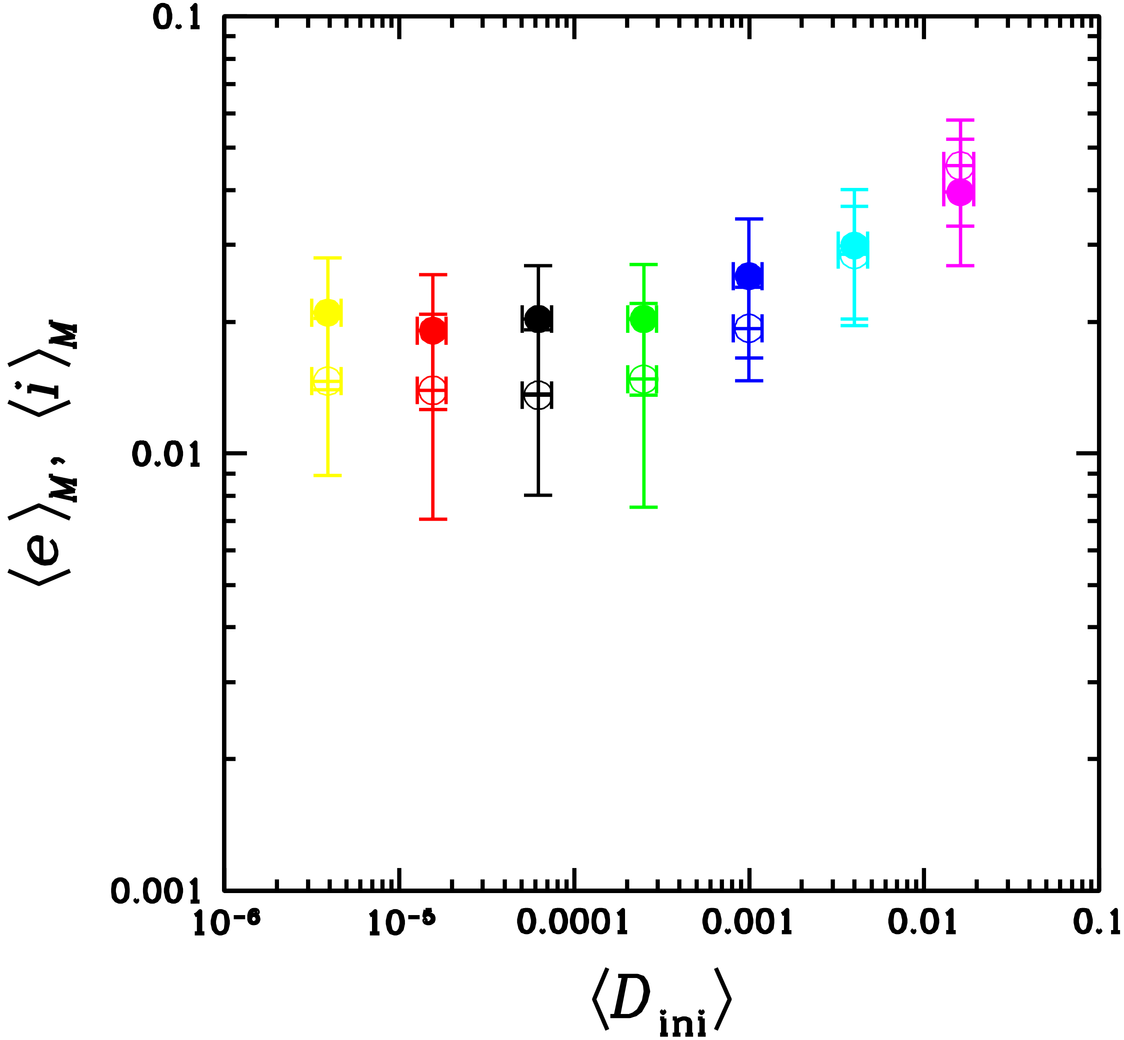


Minimum D_{fin} exists for systems formed by GIs!

$D_{\rm ini}$-Dependence

$\Sigma_1 = 10$, $\alpha = 3/2$, $r = 0.1$-$0.3\,\mathrm{AU}$, $b = 10 r_{\rm H}$, $\langle e^2 \rangle^{1/2} =$ 0.0025, 0.005, 0.01, 0.02, 0.04, 0.08, 0.16

$\langle e \rangle_M$: filled, $\langle i \rangle_M$: open



i-damping is less effective for large $D_{\rm ini}$

Minimum System AMD

$D_{\rm ini} < D_{\rm min}$

- gravitational relaxation and collisions
- $D_{\rm fin} = D_{\rm min}$, $\langle i \rangle_M / \langle e \rangle_M \simeq 0.7$ ($>$ equilibrium by gravitational relaxation)

$D_{\rm ini} > D_{\rm min}$

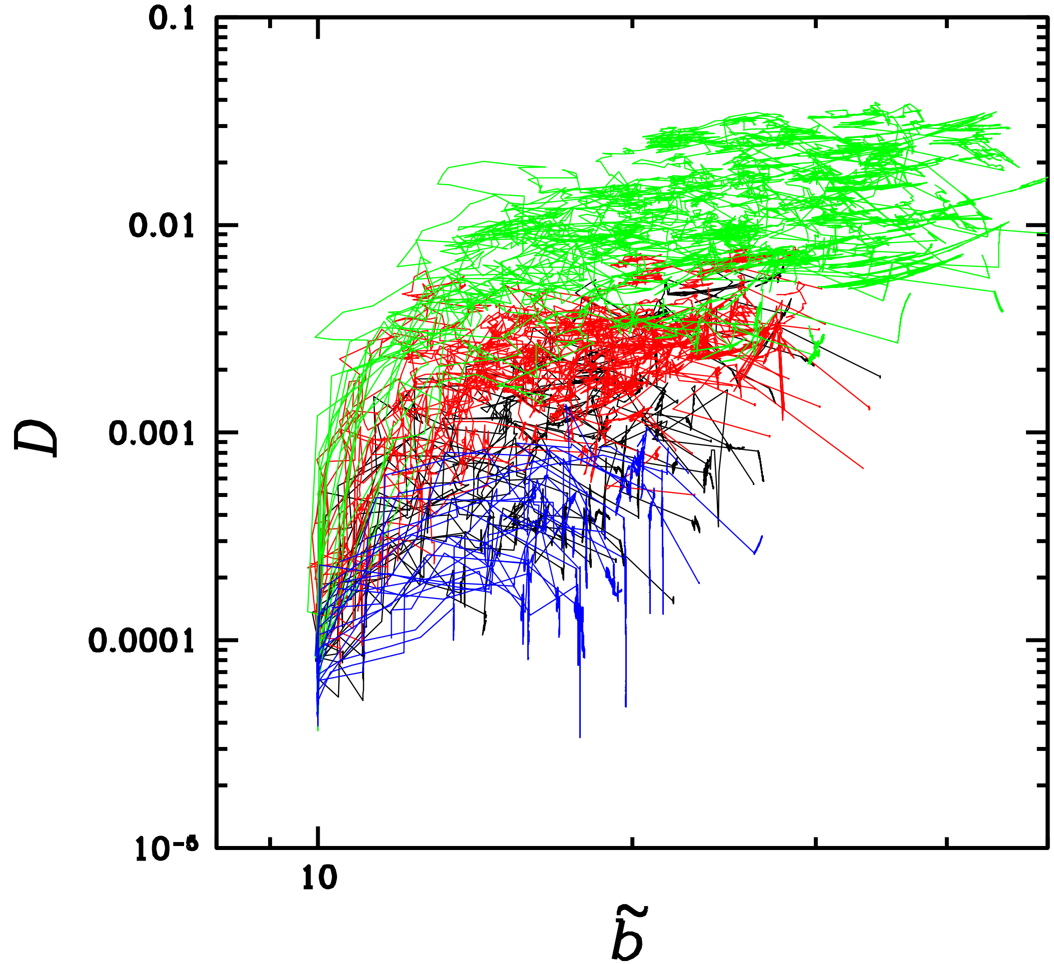
- collisions dominant
- $D_{\rm fin} < D_{\rm ini}$, $\langle i \rangle_M / \langle e \rangle_M \gtrsim 0.7$

Anisotropic Velocity Dispersion

- inclination damping is less effective than eccentricity damping (Matsumoto & EK in prep.)

Orbital Evolution (3)

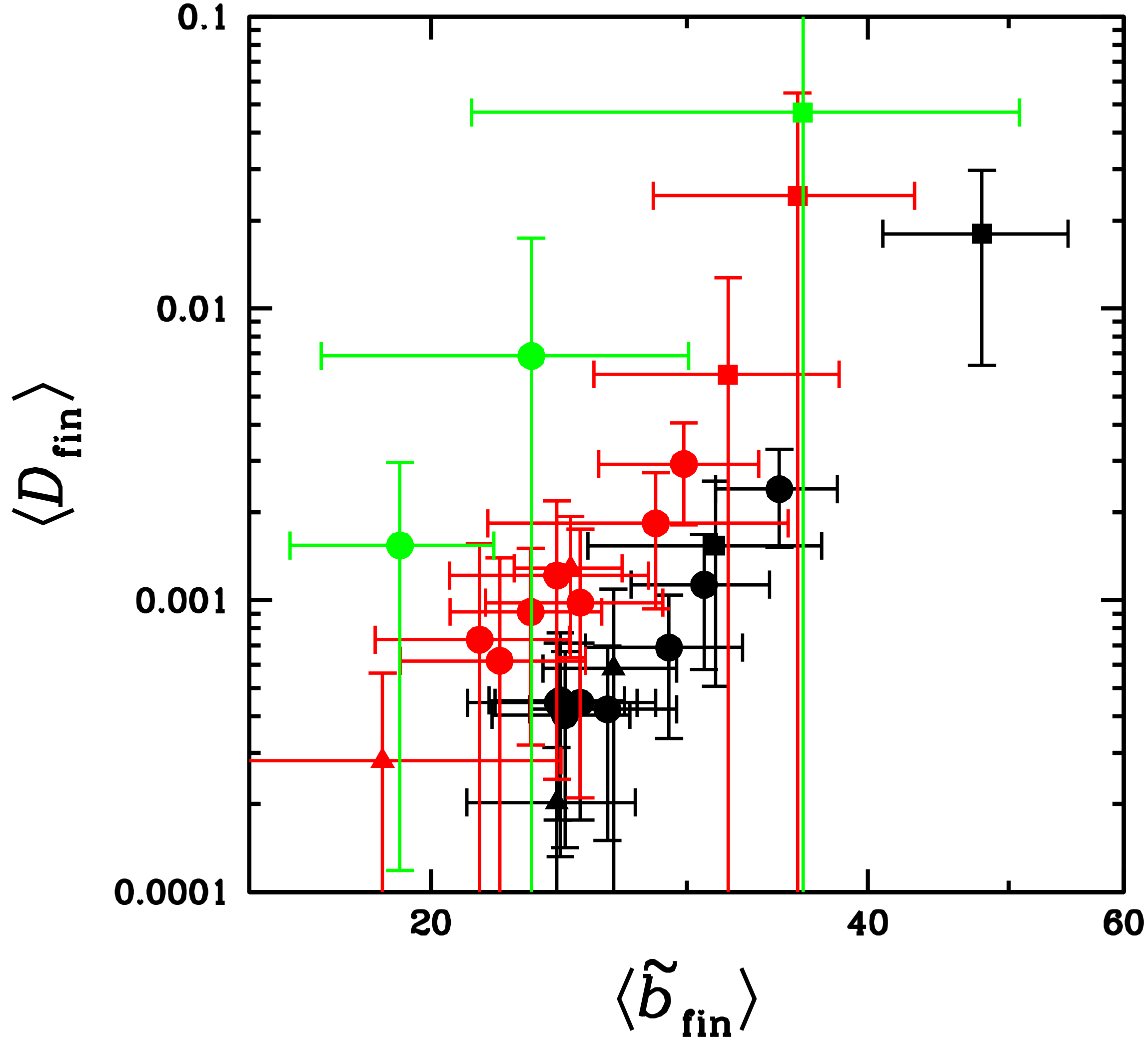
$\Sigma_1 = 10$, $\alpha = 2$, $b = 10 r_{\mathrm{H}}$, $\langle e^2 \rangle^{1/2} = 0.01$, $r =$ 0.05-0.15, 0.1-0.3, 0.2-0.6, 0.5-1.5 AU



$\tilde{r_{\mathrm{p}}}$ determines the final $(\tilde{b}, D)$

$\tilde{b}_{\rm fin}$-$D_{\rm fin}$ Relation

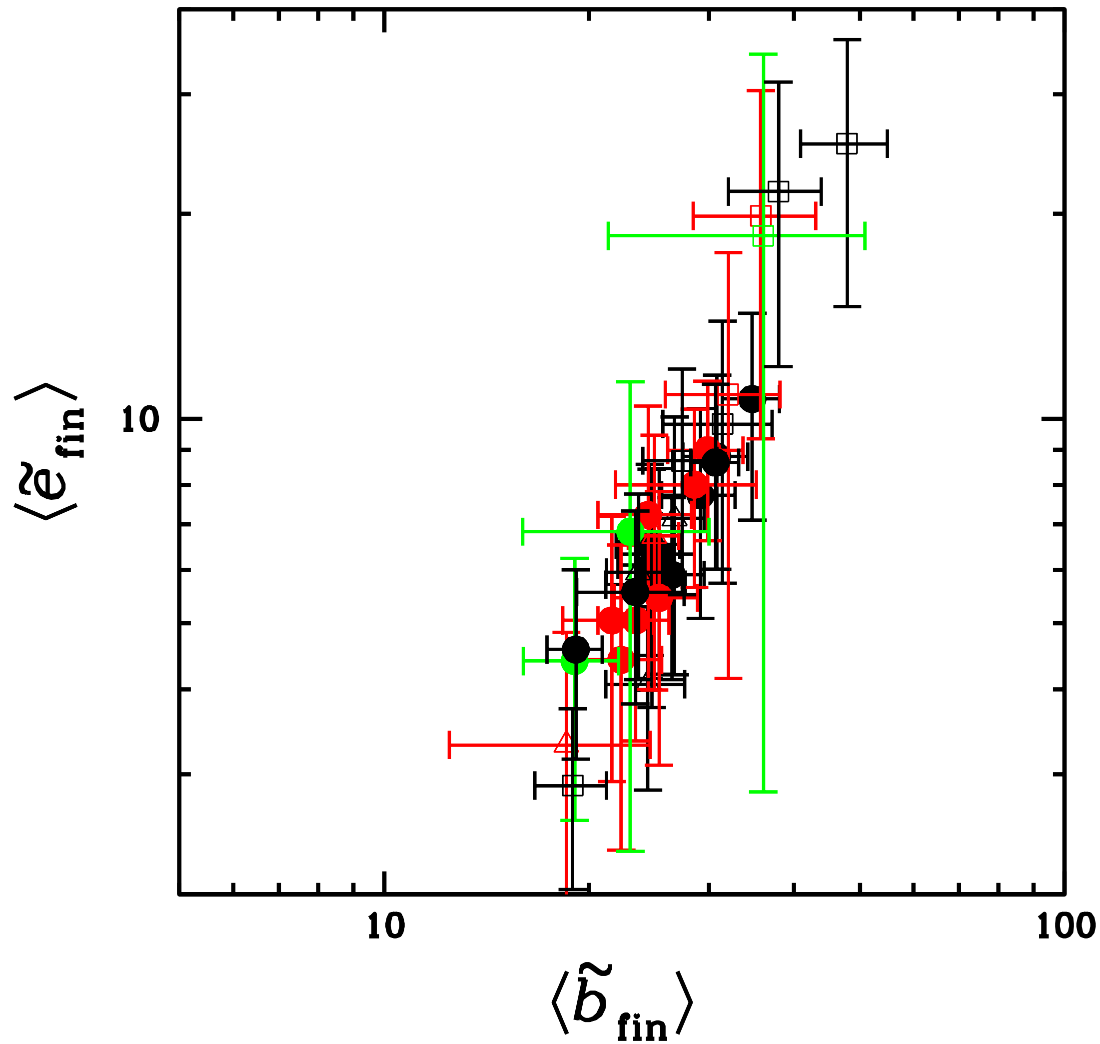
$\Sigma_1 = 10$, 30, 100, $\alpha = 3/2$-$5/2$, $b = 5$-$15 r_{\rm H}$, $r = 0.1$-$0.3, 0.2$-$0.6, 0.5$-$1.5\,{\rm AU}$



$\langle D_{\rm fin} \rangle$ increases with $\langle \tilde{b}_{\rm fin} \rangle$ (with decreasing $\tilde{r}_{\rm p}$)

$\tilde{b}_{\rm fin}$-$\tilde{e}_{\rm fin}$ Relation

$\Sigma_1 = 10$, 30, 100, $\alpha = 3/2$-$5/2$, $b = 5$-$15 r_{\rm H}$, $r = 0.05$-$0.15, 0.1$-$0.3, 0.2$-$0.6, 0.5$-$1.5\,{\rm AU}$



$\langle \tilde{e}_{\rm fin} \rangle$ increases with $\langle \tilde{b}_{\rm fin} \rangle$ (with decreasing $\tilde{r}_{\rm p}$)

$$\mathrm{d}\log\langle\tilde{e}\rangle/\mathrm{d}\log\langle\tilde{b}\rangle \simeq 2$$

Summary

Close-in Giant Impacts

- large $\tilde{r}_{\rm p} = r_{\rm p}/r_{\rm H} \rightarrow$ cold compact system
  - mass: comparable
  - orbit: $b \simeq 20$-$30 r_{\rm H}$, $e, i \lesssim 0.04$ ($D \lesssim 0.001$), non-resonant (consistent with observations)

Orbital Architecture

- minimum D for systems formed by giant impacts
- $\tilde{r}_{\rm p}(a) \rightarrow \tilde{b}$, $\tilde{e}$ ($\tilde{e} \propto \tilde{b}^2$)

Future Works

- comparison with the observation (Isoe+ in prep.)
- physical interpretation of the architecture: system instability timescale $t_{\rm inst}(\tilde{b}, \tilde{e})$
- collisional orbital evolution (Matsumoto+ 2015; Matsumoto & EK in prep.)