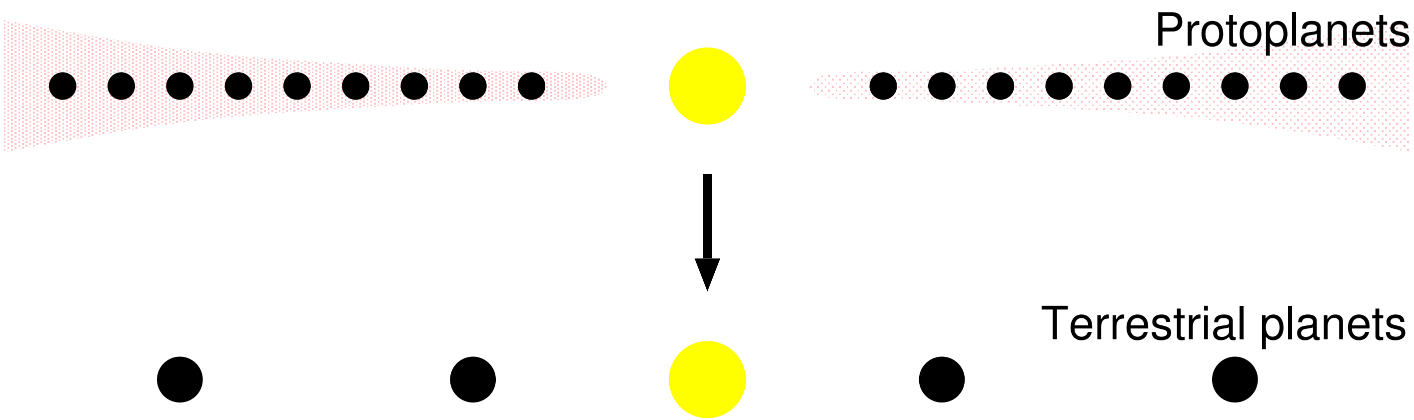
The Final Stage of Terrestrial Planet Formation



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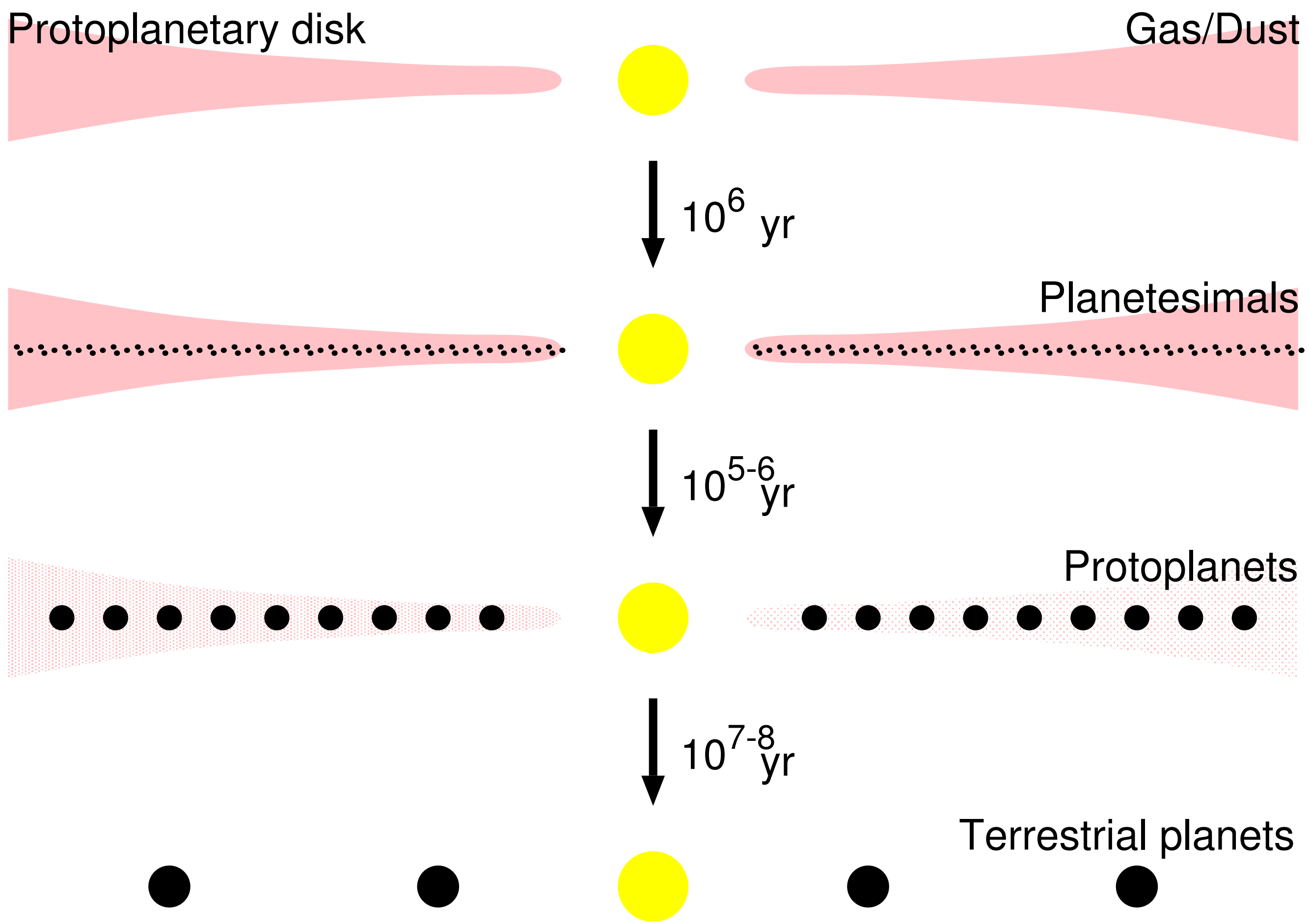
Terrestrial Planet Formation

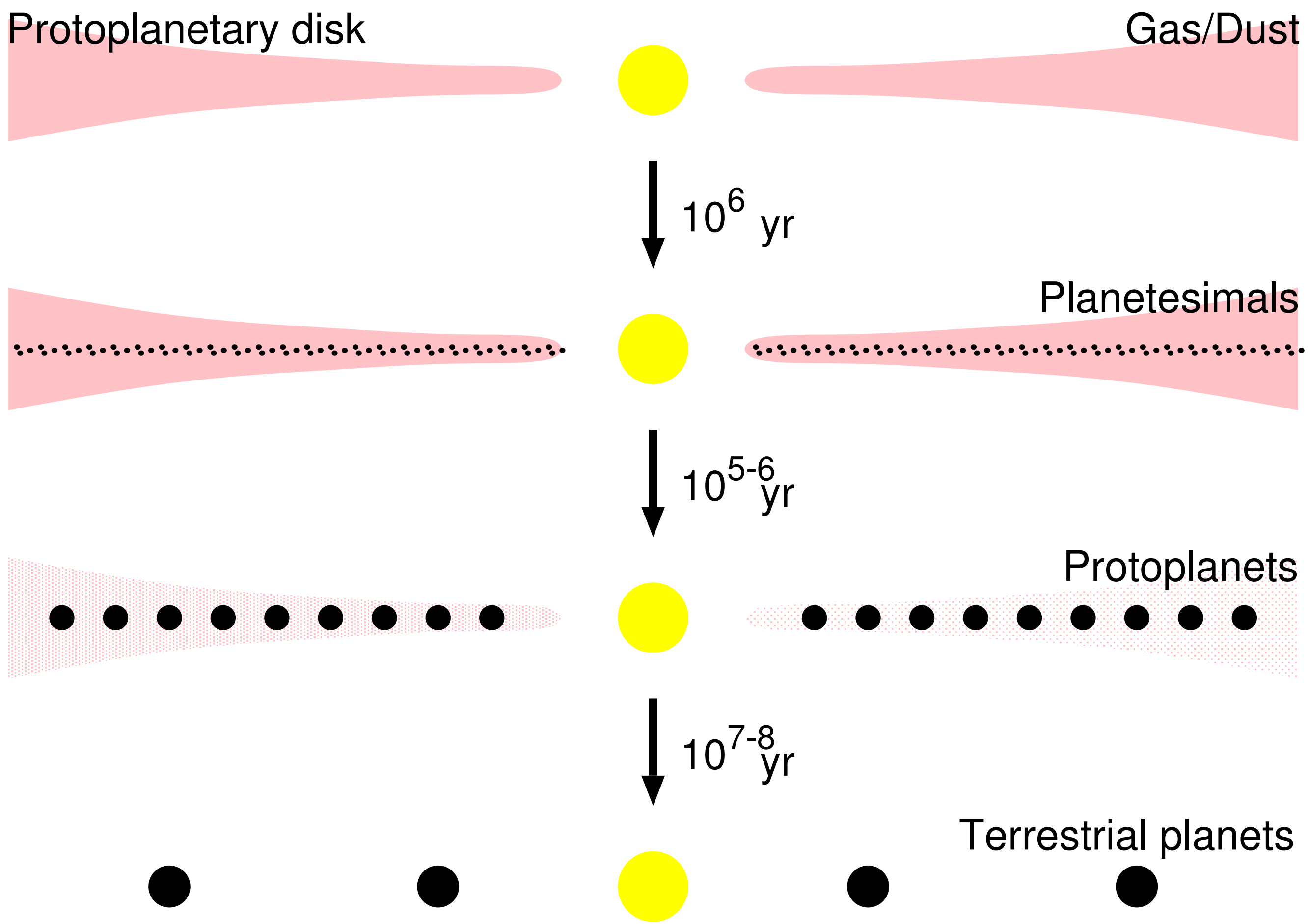


Act 1 Dust to planetesimals (gravitational instability/binary coagulation)

Act 2 Planetesimals to protoplanets (runaway-oligarchic growth)

Act 3 Protoplanets to terrestrial planets (giant impacts)

Terrestrial Planet Formation



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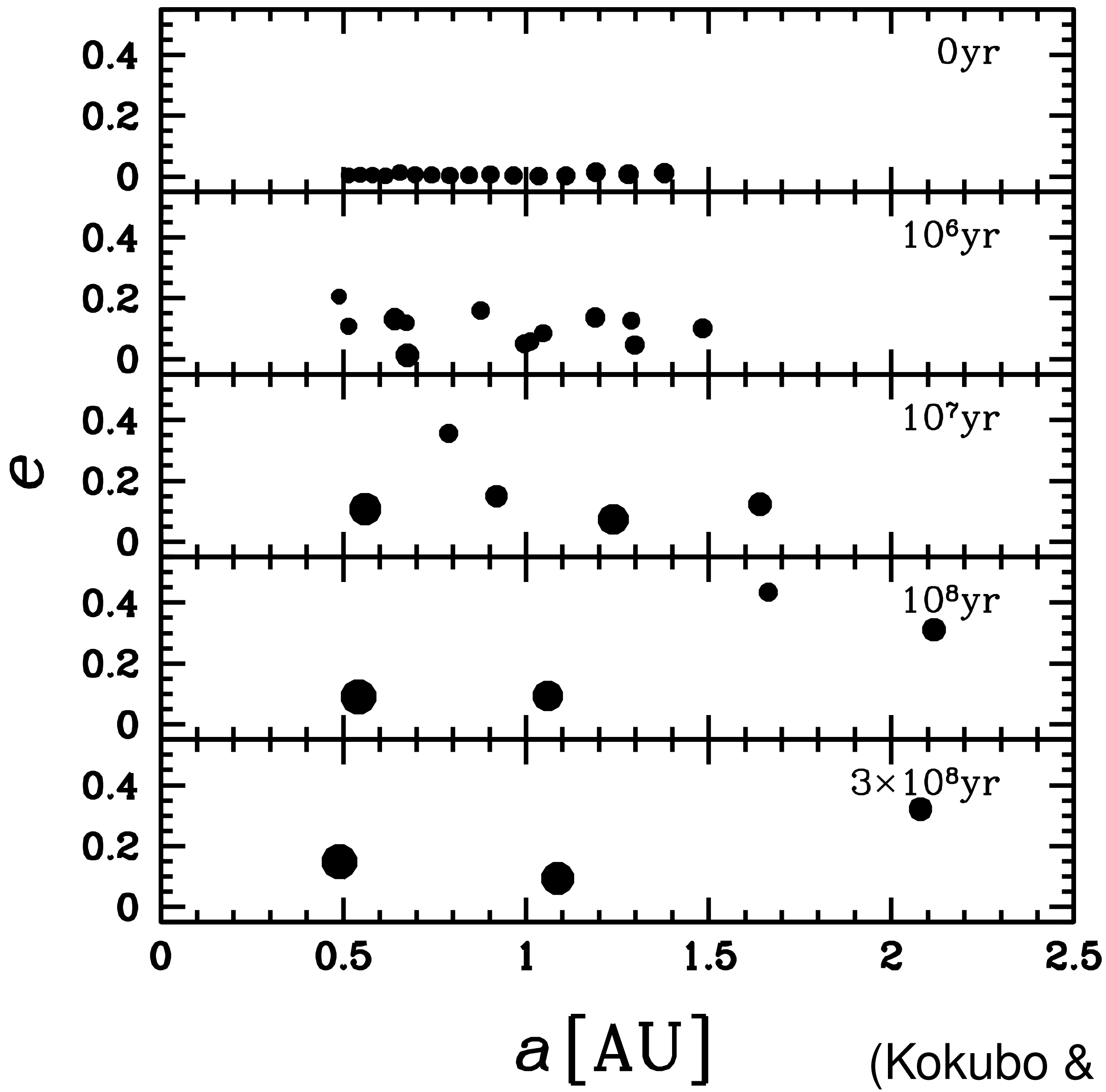
Simulation of Giant Impact Stage

standard disk model with realistic accretion condition



(Kokubo & Genda 2010)

An Unsolved Problem

High *e* and *i* of Planets

N-body simulations

- $e, i \simeq 0.1$
  (e.g., Chambers & Wetherill 1998; Agnor+ 1999; Kokubo+ 2006)

Solar system

- Venus and Earth: $e, i \simeq 0.01$

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What is missing?

Recent Progress

Collision Experiments (SPH Simulations)

- Accretion condition
- Collisional debris production

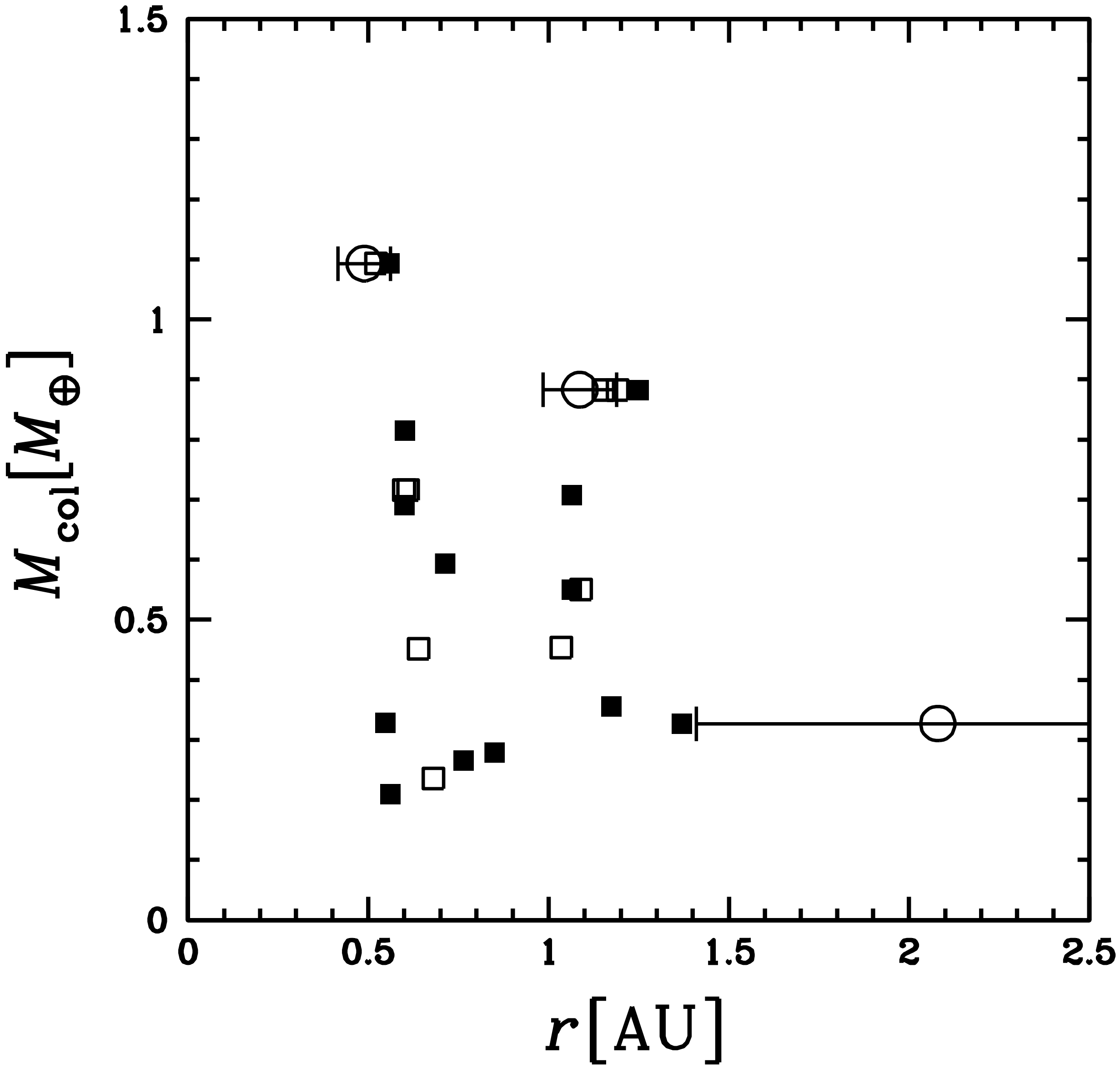
(Genda, Kokubo & Ida 2011)

Accretion Experiments (*N*-Body Simulations)

- 50% of collisions are not accretionary but hit-and-run
- Growth timescale: $\simeq 10^8$ yr
- Collisions take place locally around a planet

(Kokubo & Genda 2010)

Location and Mass of Collisions



■: accretionary, □: hit-and-run, ◯: planets

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10% of the total mass goes to collisional debris!

The final stage: planet-debris interaction?

N-Body Simulation

Model

- planet: uniform sphere
- disk: gas-free
- collision: realistic accretion condition (Genda+ 2011)

Integration Method

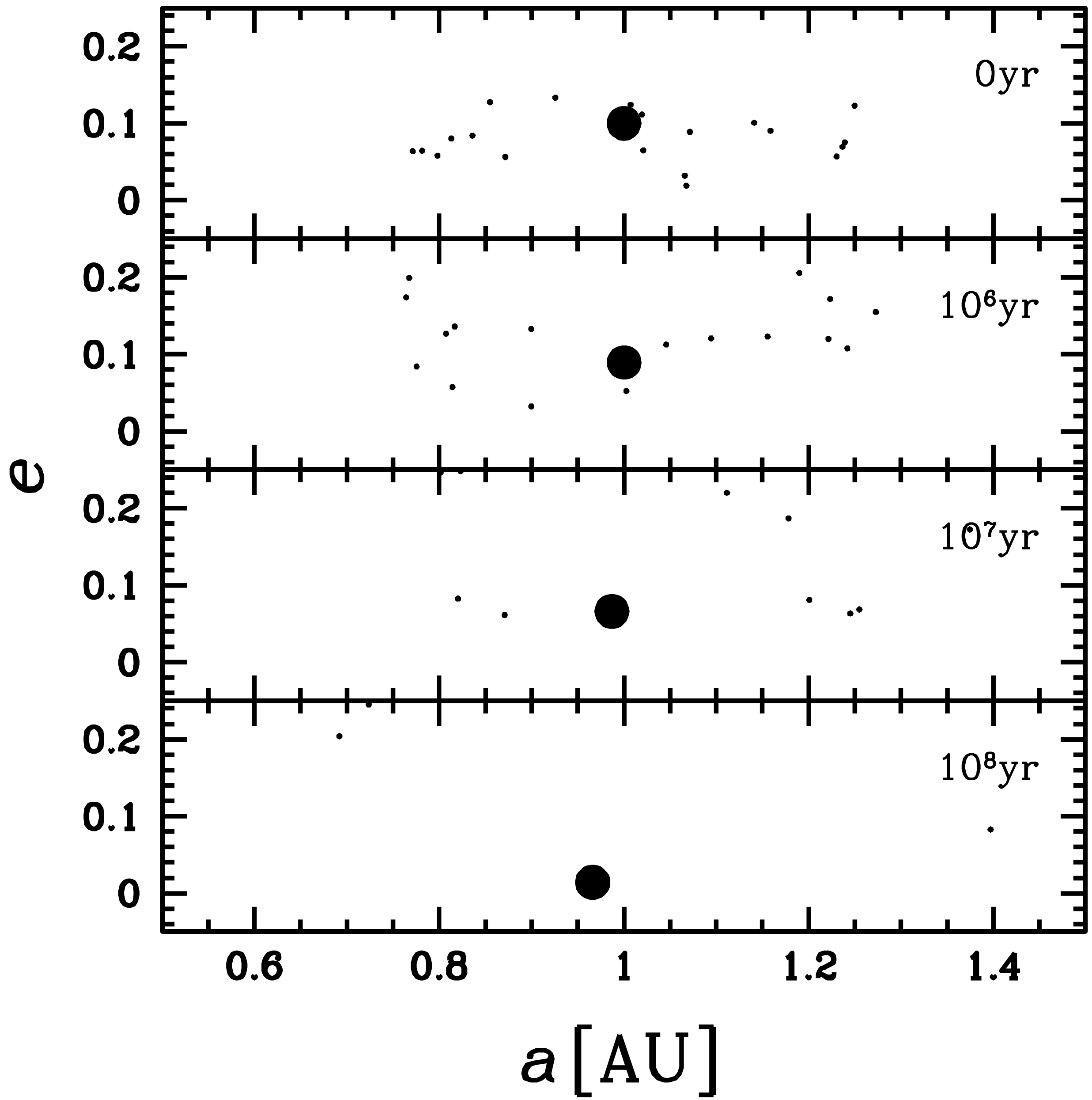
- modified Hermite integrator for planetary dynamics (Kokubo & Makino 2004)
- phantom-GRAPE (Nitadori+ 2006)

Initial Condition

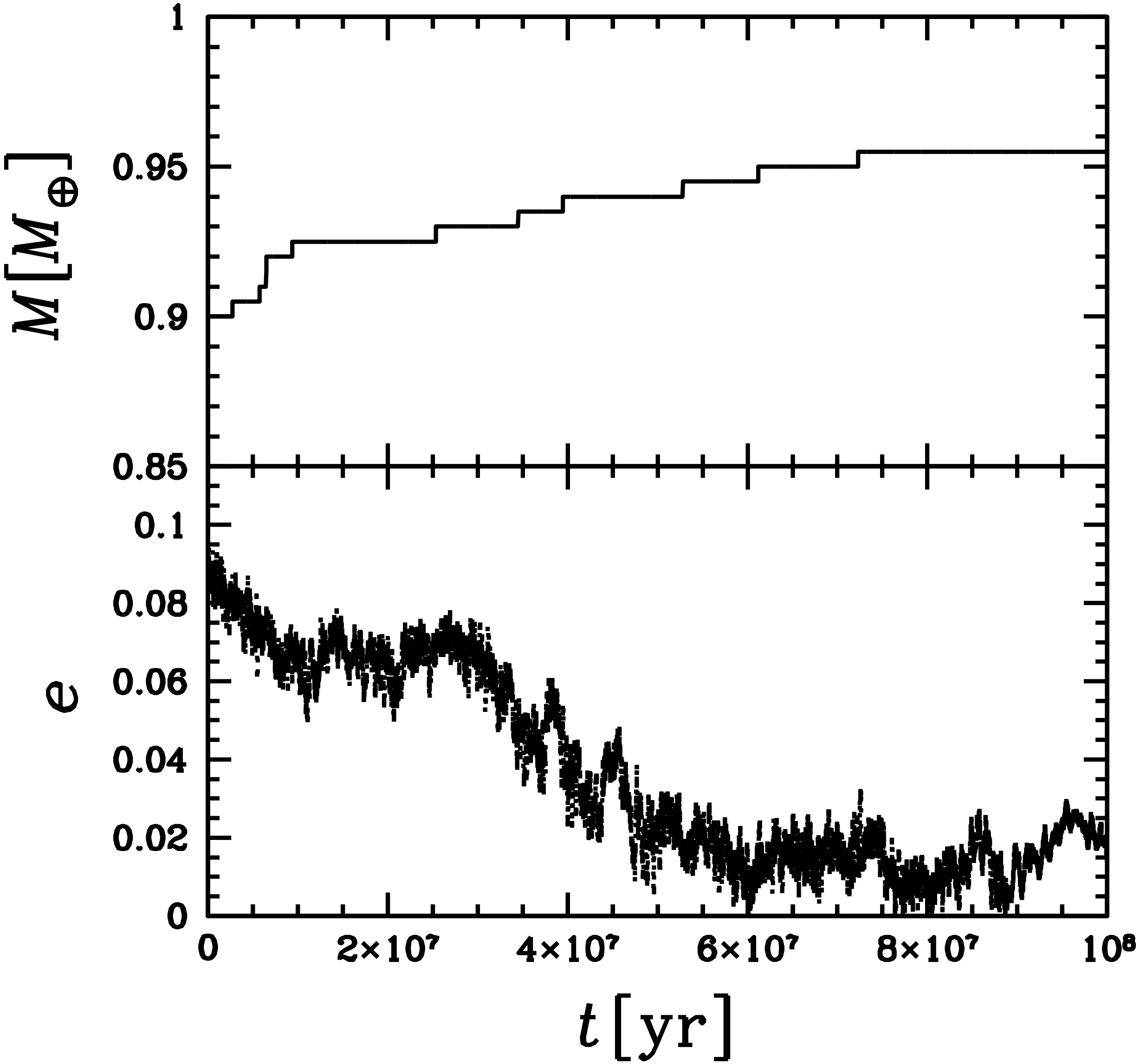
	n	$M(M_\oplus)$	a(AU)	e	i
planet	1	0.8-0.95	1	0.1	0
debris	10-40	0.05-0.2	0.75-1.25	0.1	0.1

An Example Run

$M = 0.9M_\oplus$, $e = 0.1$; $M_\mathrm{d} = 0.1M_\oplus$, $n = 20$, $\langle e_\mathrm{d}^2 \rangle^{1/2} = \langle i_\mathrm{d}^2 \rangle^{1/2} = 0.1$

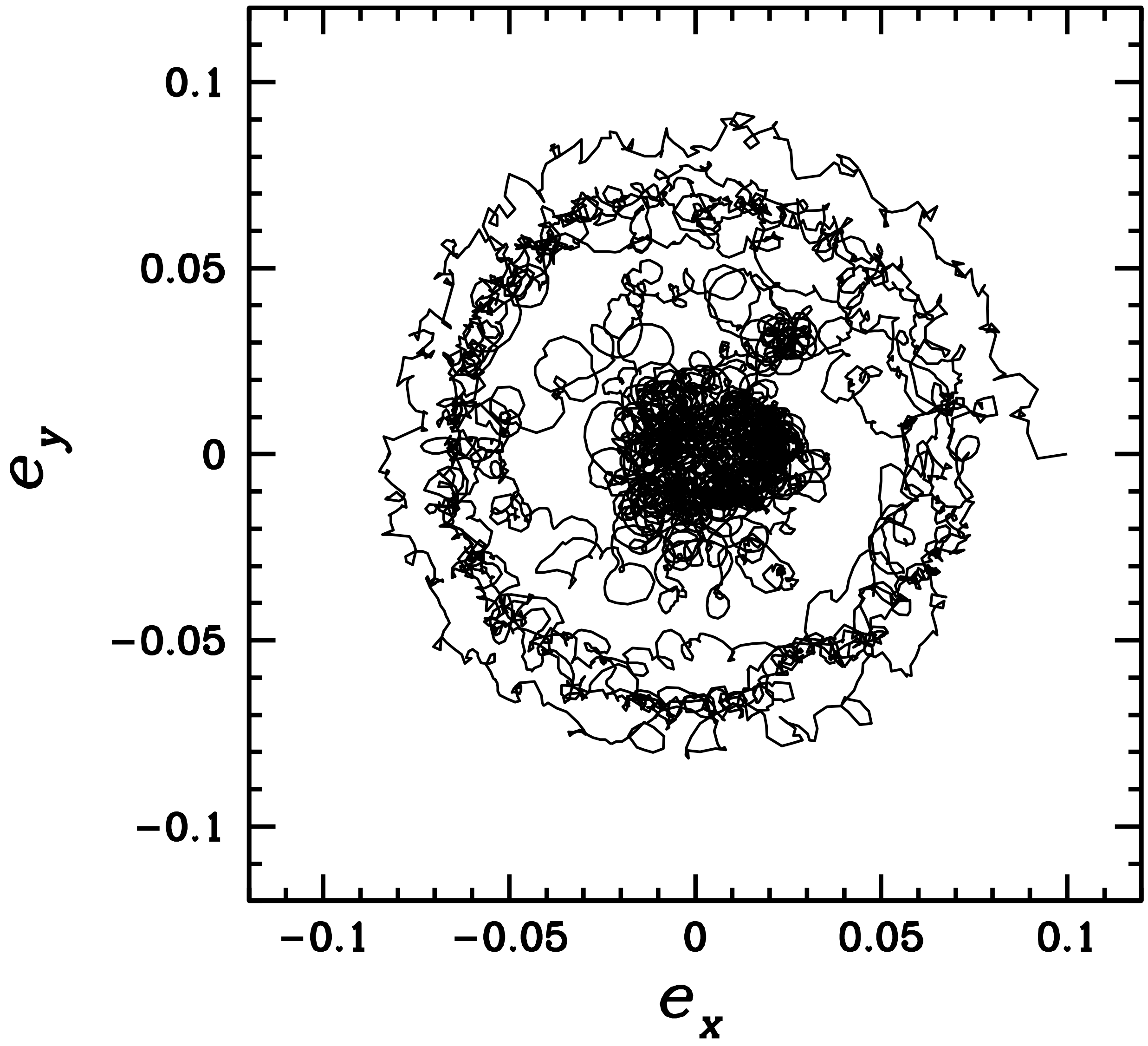


Mass and Eccentricity Evolution



$e = 0.014\ (10^8\ \mathrm{yr})$

Eccentricity Vector Evolution



perturbation circle (secular interaction) + e-damping

Dynamical Friction

Chandrasekhar's Formula

A large particle with M and v_M in a swarm of small particles with m and v_m

$$\frac{1}{v_M}\frac{\mathrm{d}v_M}{\mathrm{d}t} \sim \frac{G^2 M m n_m}{v_M^3}$$

$$(v_M > v_m)$$

Application to a Particle Disk

$$\frac{1}{e_M}\frac{\mathrm{d}e_M}{\mathrm{d}t} \sim \frac{G^2 M m n_{\mathrm{s},m}}{2 i_m a e_M^3 a^3 \Omega^3} \sim \frac{G^2 M \Sigma}{e_M^4 a^4 \Omega^3}$$

$$(\Sigma = m n_{\mathrm{s},m},\ v_M \simeq e_M a\Omega,\ n_m \simeq n_{\mathrm{s},m}/2a i_M,\ i_m < i_M)$$

$$t_{\mathrm{DF}} \equiv \frac{e_M}{\mathrm{d}e_M/\mathrm{d}t} \sim \frac{e_M^4 a^4 \Omega^3}{G^2 M \Sigma}$$

DF from Collisional Debris

Planet Eccentricity

- model: equal-mass debris $m = M_\mathrm{d}/n$ (M_d: total debris mass, n: number)
- assumption: $M_\mathrm{d} \gg M$, $n \gg 1$ (M: planet mass)
- energy equiparation (e: planet eccentricity, e_d: debris eccentricity)

$$Me^2 = me_\mathrm{d}^2 \to e = \left(\frac{m}{M}\right)^{1/2} e_\mathrm{d} = \left(\frac{M_\mathrm{d}}{M}\right)^{1/2} n^{-1/2} e_\mathrm{d}$$

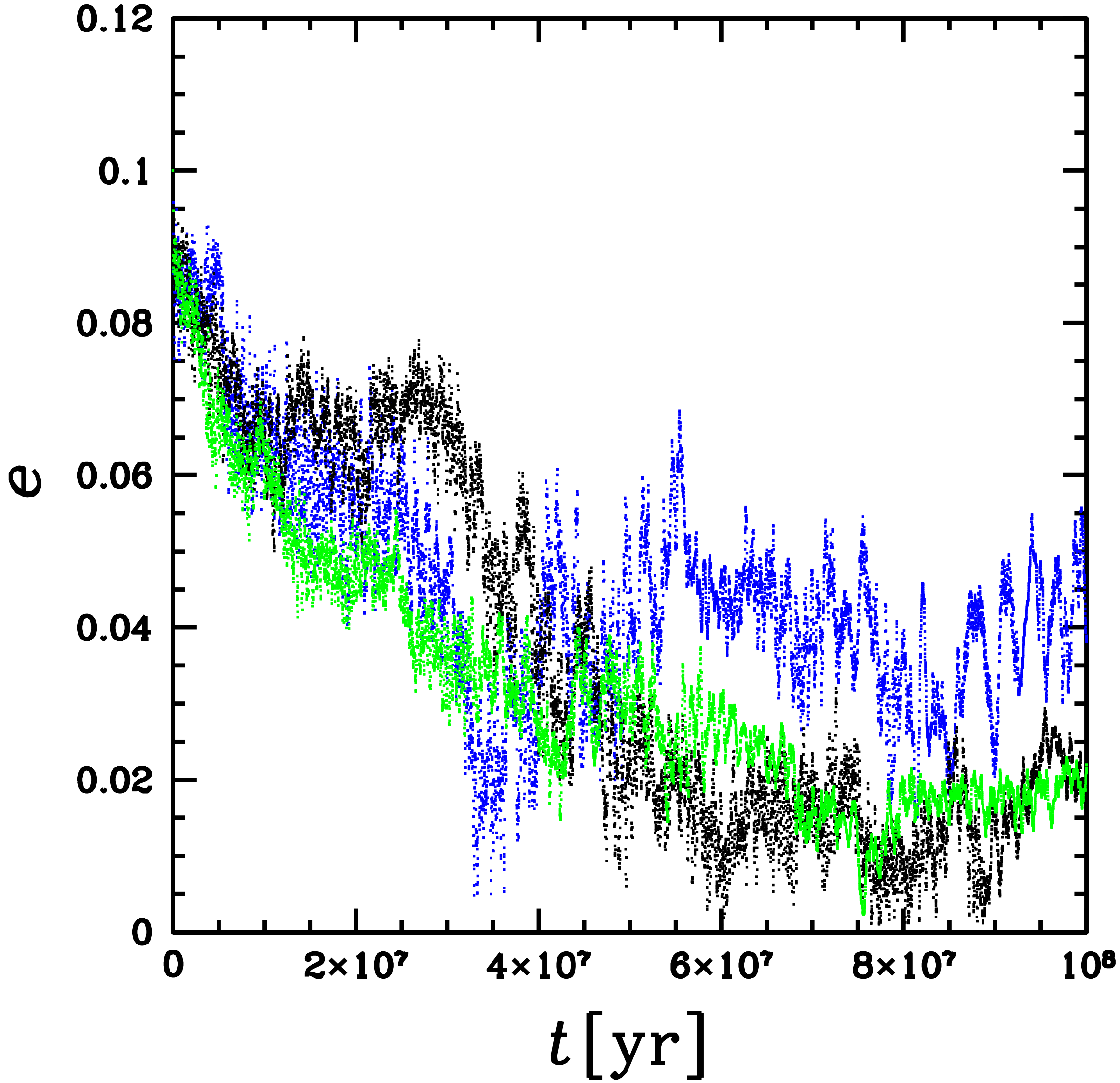
e-Damping Timescale

- assumption: $Me^2 \gg me_\mathrm{d}^2$, $n \gg 1$
- timescale (Δa: debris ring width, a: semimajor axis)

$$t_\mathrm{DF} \sim 10^4 \left(\frac{M}{M_\oplus}\right)^{-1} \left(\frac{e}{0.1}\right)^4 \left(\frac{M_\mathrm{d}}{0.1M_\oplus}\right)^{-1} \left(\frac{\Delta a}{0.5\mathrm{AU}}\right) \left(\frac{a}{1\mathrm{AU}}\right)^{1/2} \mathrm{yr}$$

Dependence on *n*

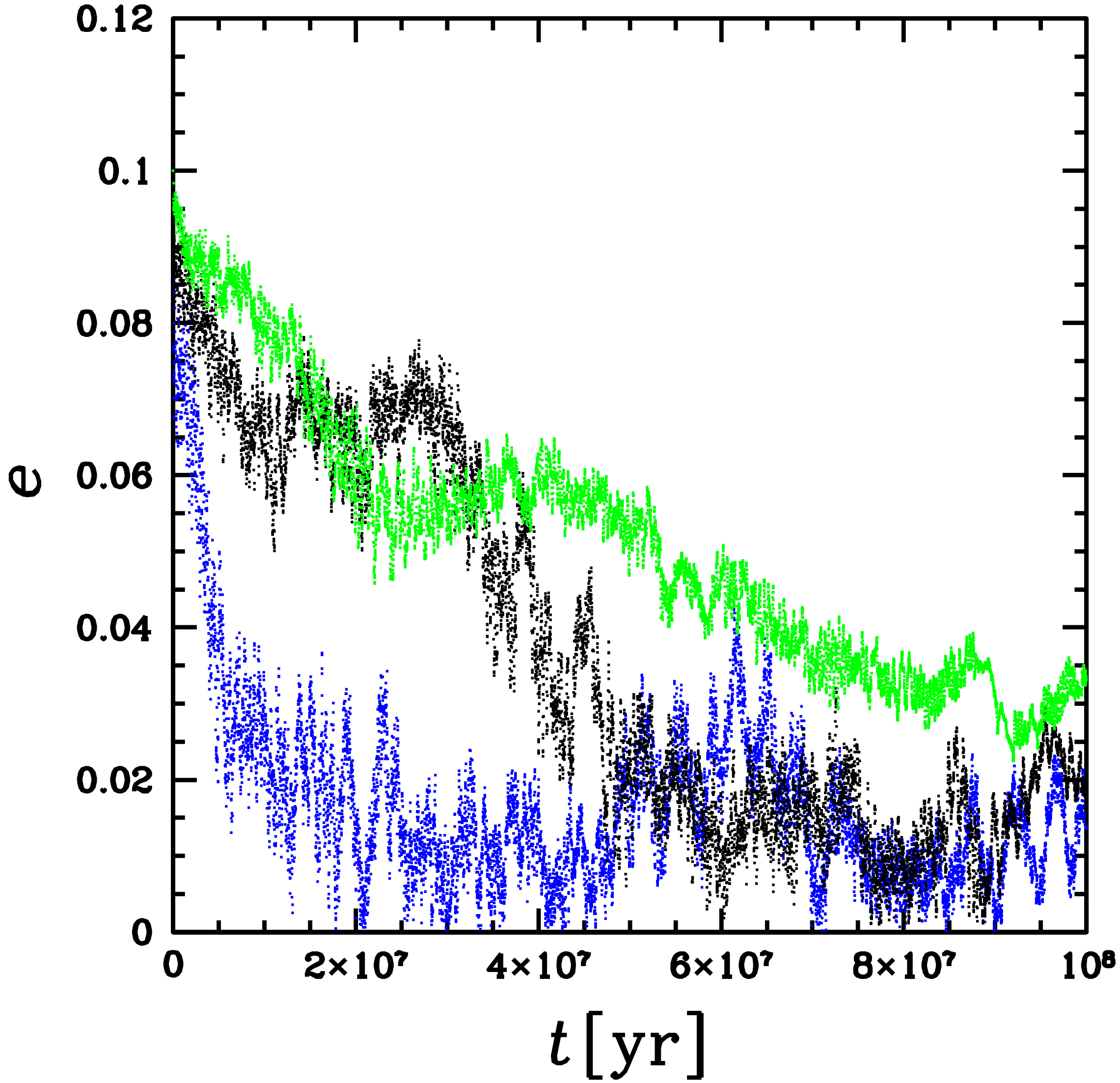
$n = 10, 20, 40$ ($M_{\rm d} = 0.1 M_\oplus$)



$t_{\rm DF} \simeq$ const., fluctuation $\propto n^{-1/2}$

Dependence on M_d

$M_\mathrm{d} = 0.05 M_\oplus, 0.1 M_\oplus, 0.2 M_\oplus \; (M + M_\mathrm{d} = M_\oplus)$



$t_\mathrm{DF} \propto M_\mathrm{d}^{-1}$

Summary

Collisional Debris Production by Giant Impacts

- debris mass: $M_{\rm d} \simeq 0.1 M_{\rm sys}$
- debris distribution: locally around a planet orbit

"Dynamical Friction" on a Planet from Debris

- $M_{\rm d} \gtrsim 0.1 M_{\oplus}$, $n \gtrsim 20 \Rightarrow e : 0.1 \rightarrow 0.01$
- $t_{\rm DF} \sim 10^8\,{\rm yr}$

Planetary orbits are inevitably circularized by debris after giant impacts!?

Future (Ongoing) Works

- *N*-body simulation with debris production
- Observational possibility of collisional debris