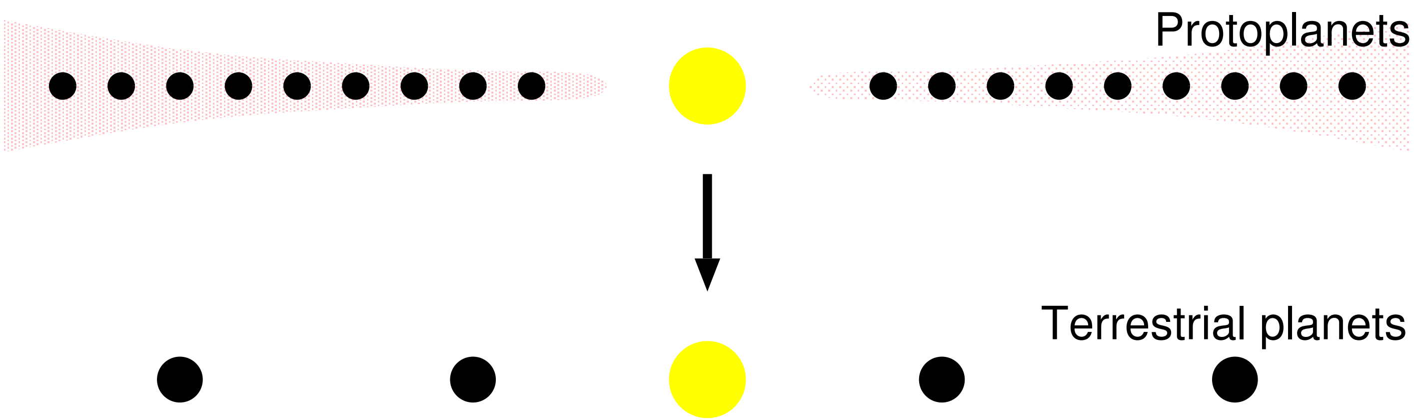
The Final Stage of Terrestrial Planet Formation



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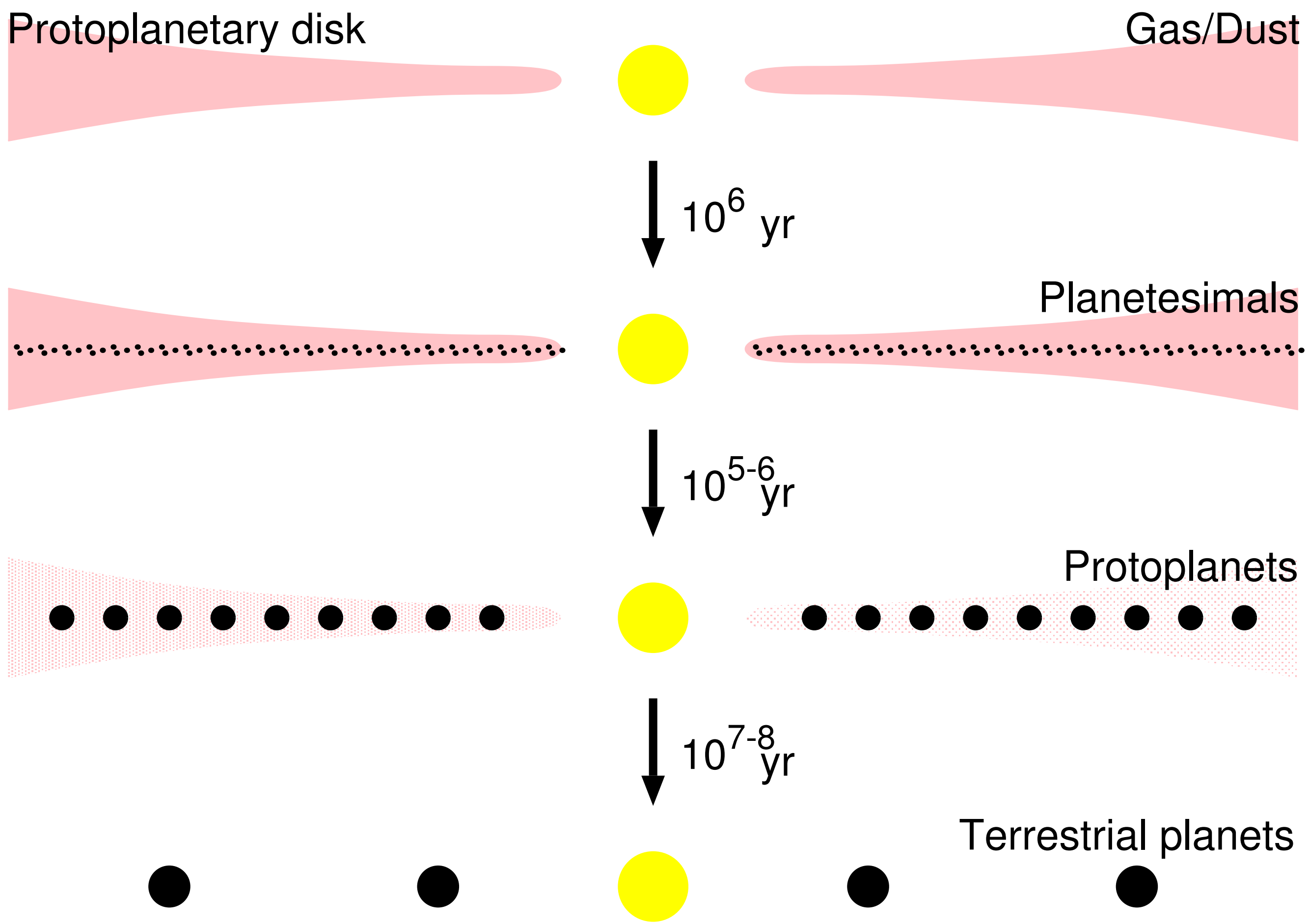
Terrestrial Planet Formation

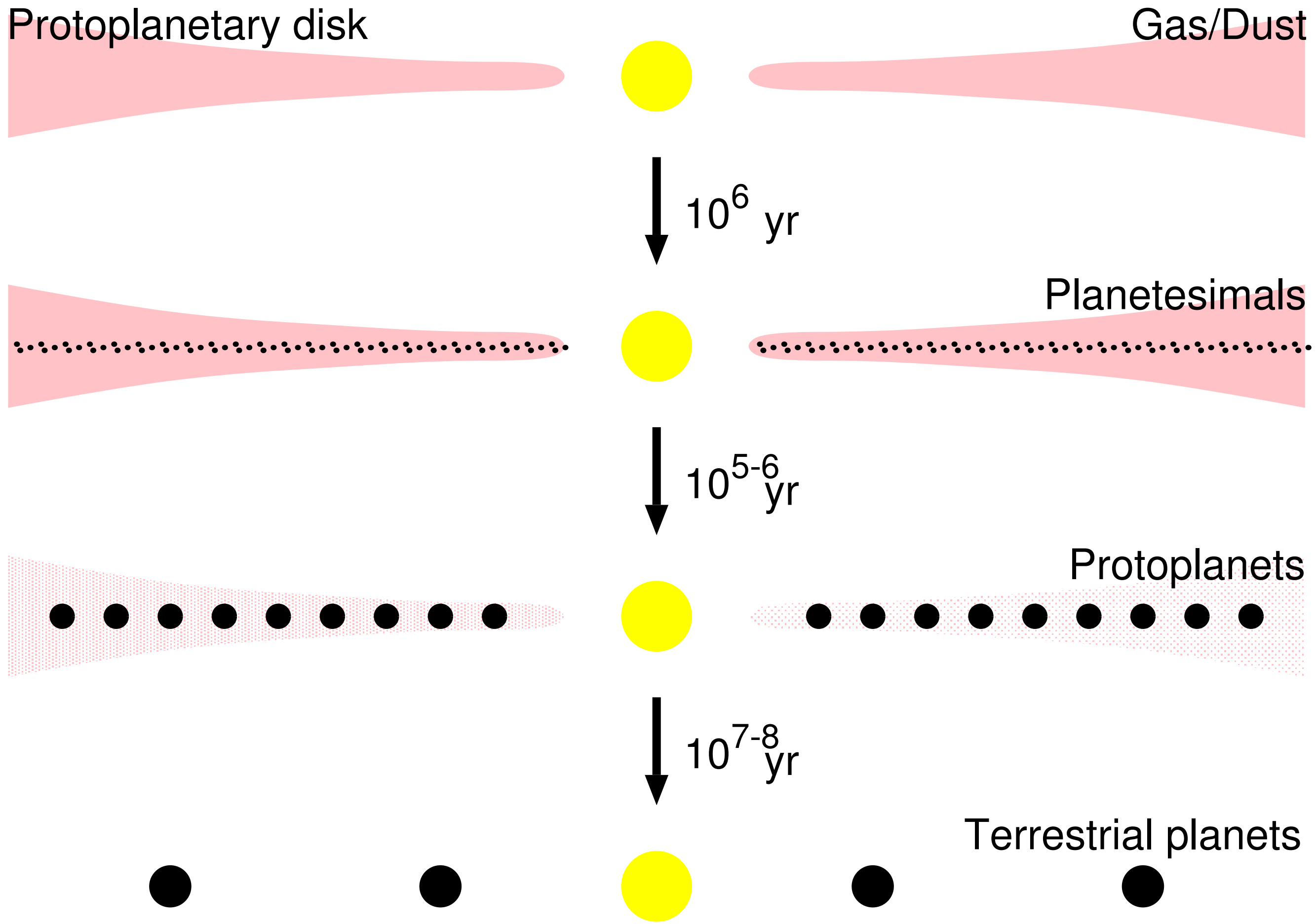


Act 1 Dust to planetesimals (gravitational instability/binary coagulation)

Act 2 Planetesimals to protoplanets (runaway-oligarchic growth)

Act 3 Protoplanets to terrestrial planets (giant impacts)

Terrestrial Planet Formation



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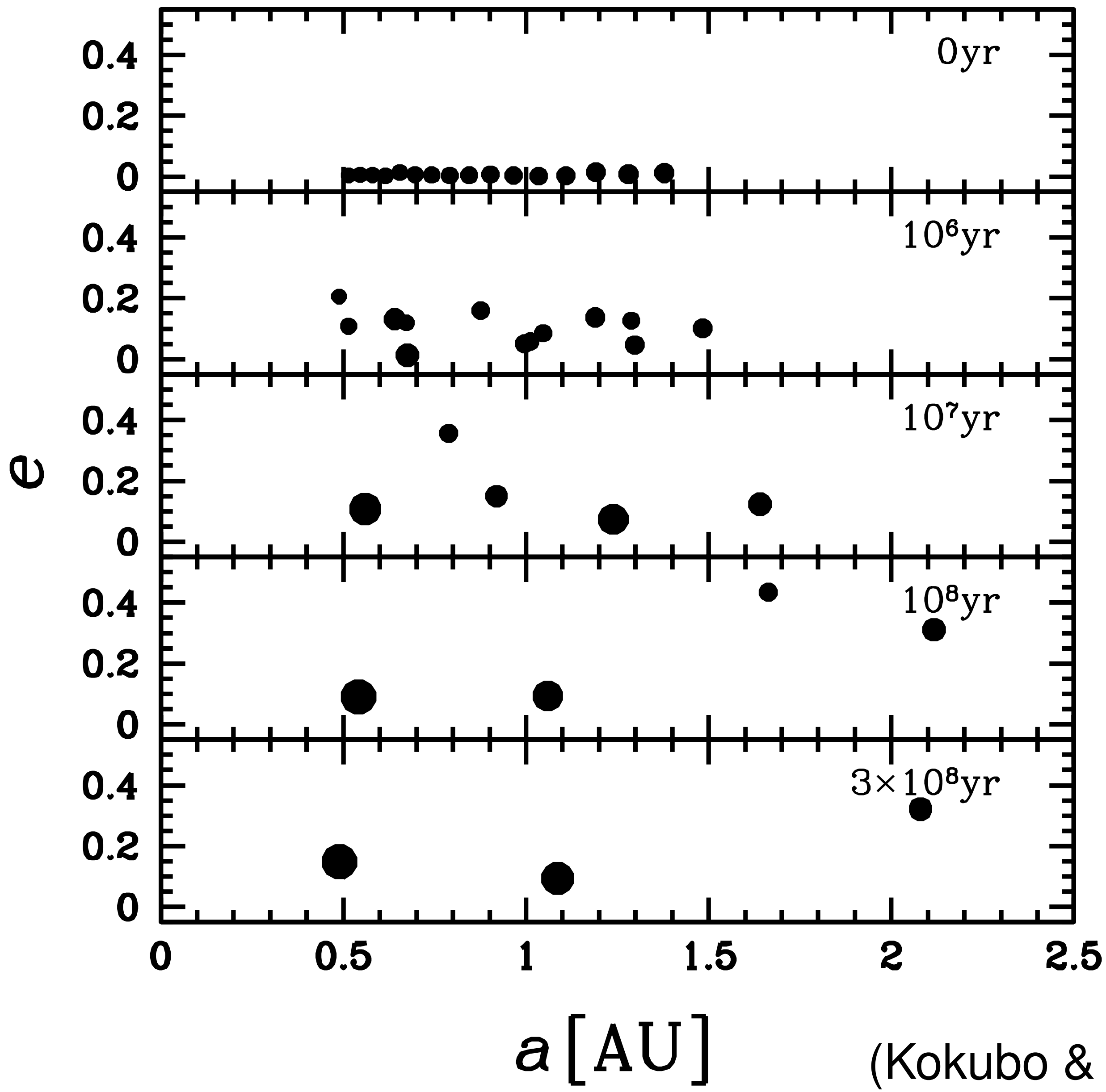
Simulation of Giant Impact Stage

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

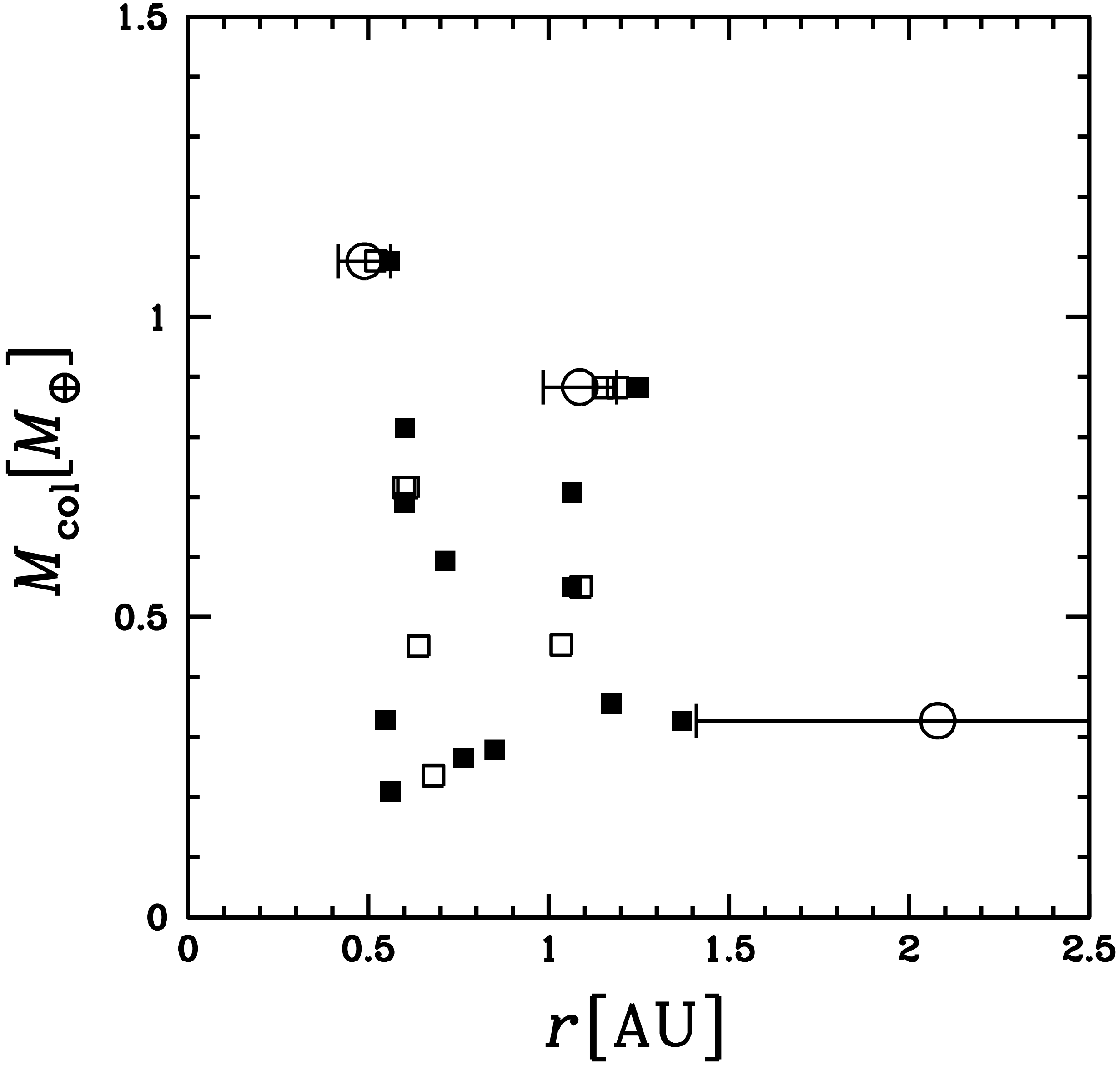
(Genda, Kokubo & Ida 2011)

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

Modified Hermite Integrator

Hermite Integrator

- 4th-order PEC-type integrator
- time-symmetric: no secular errors in a and e
- secular error in ω

(Makino & Aarseth 1992)

Modified Hermite Integrator for Planetary Dynamics

- "magic number" coefficient of the highest-order term $\rightarrow$ 2-order small secular error in ω

(Kokubo & Makino 2004)

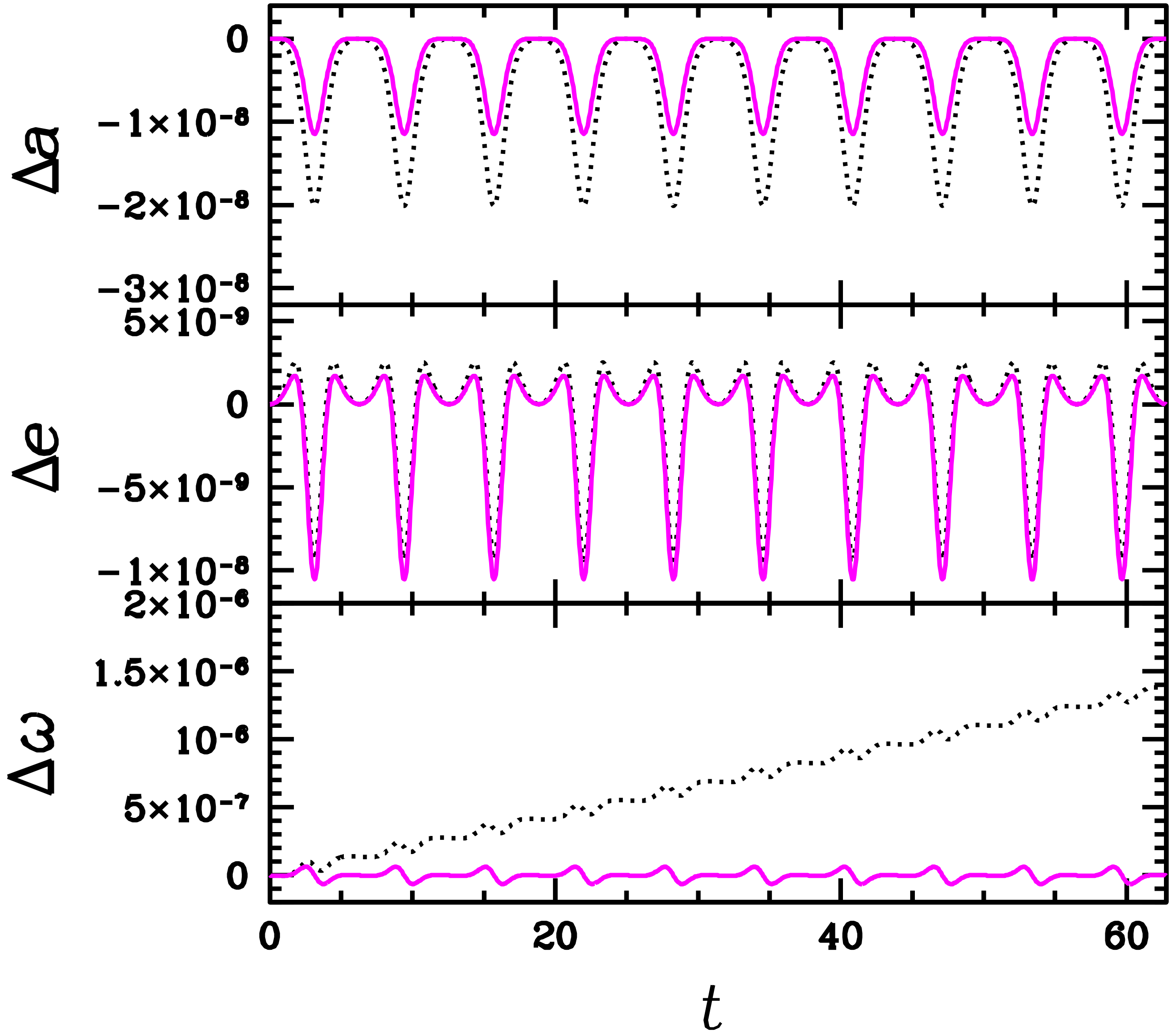
$$\boldsymbol{v}_1 = \boldsymbol{v}_0 + \boldsymbol{a}_0 \Delta t + \frac{1}{2}\dot{\boldsymbol{a}}_0 \Delta t^2 + \frac{1}{6}\boldsymbol{a}_0^{(2)} \Delta t^3 + \frac{1}{24}\boldsymbol{a}_0^{(3)} \Delta t^4$$

$$\boldsymbol{x}_1 = \boldsymbol{x}_0 + \boldsymbol{v}_0 \Delta t + \frac{1}{2}\boldsymbol{a}_0 \Delta t^2 + \frac{1}{6}\dot{\boldsymbol{a}}_0 \Delta t^3 + \frac{1}{24}\boldsymbol{a}_0^{(2)} \Delta t^4 + \frac{\alpha}{120}\boldsymbol{a}_0^{(3)} \Delta t^5$$

$$\alpha : 1 \rightarrow \frac{7}{6}$$

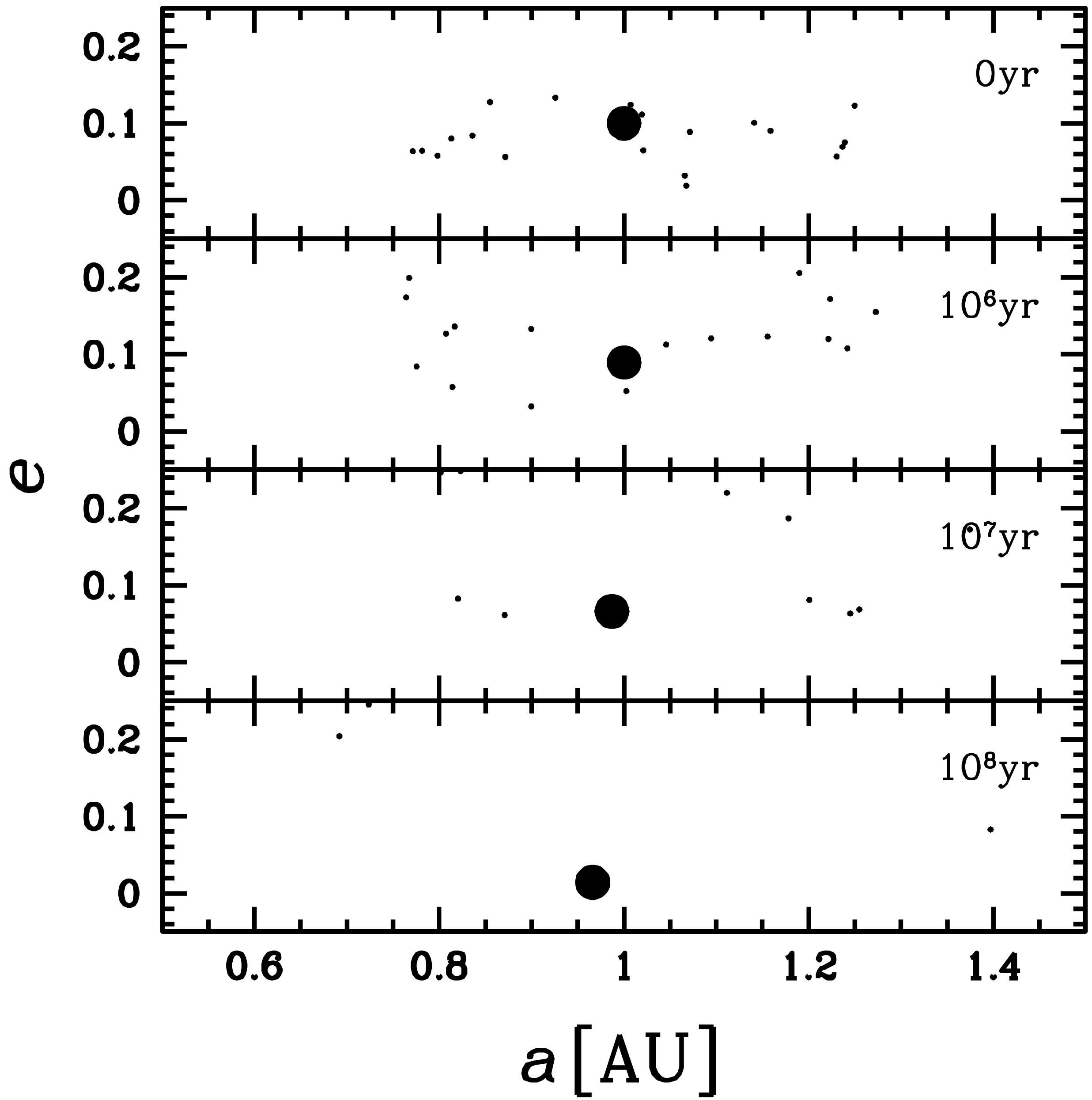
Errors in Kepler Orbits

standard ($\alpha = 1$): dotted , modified ($\alpha = 7/6$): solid

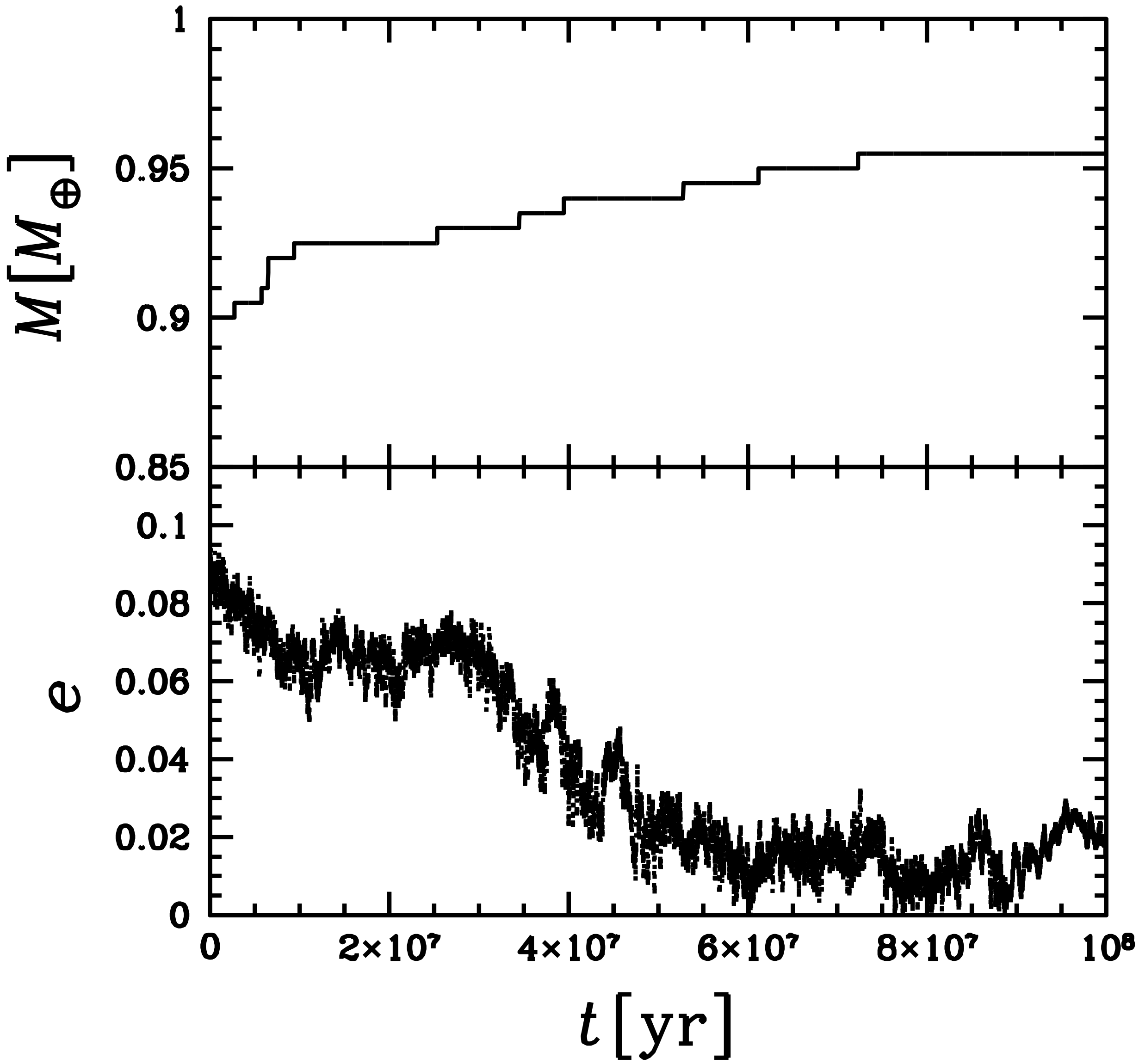


An Example Run

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



Mass and Eccentricity Evolution



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

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)

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

e-Damping Timescale

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

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

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

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

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

Future (Ongoing) Works

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