Growing Earth: *N*-body simulations of terrestrial planet formation

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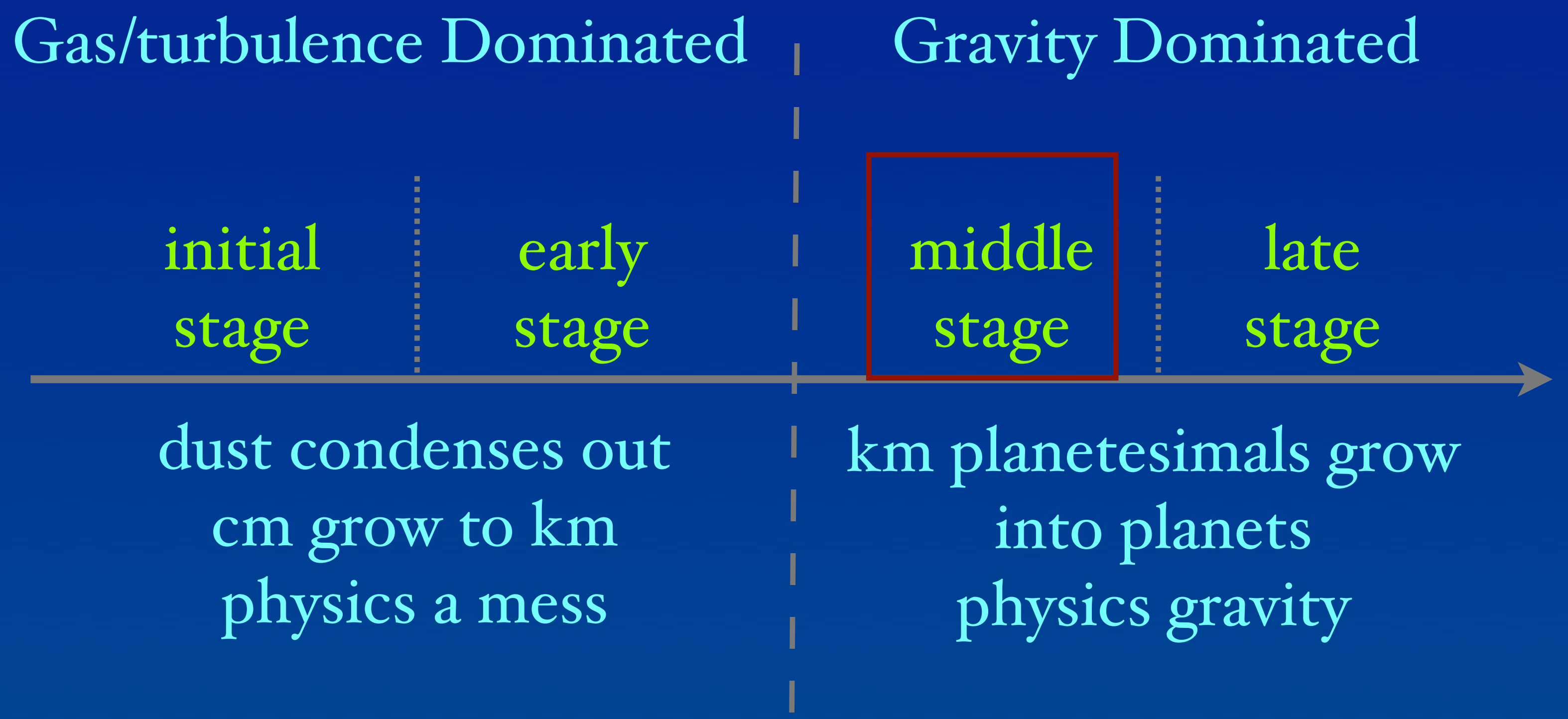
Outline

- Review of Planet Formation Paradigm
- Previous Work (Semi-analytic and Direct)
- Numerical Method
  - Planetesimal Structure Model
  - Planetesimal Collision Model
  - Planetesimal Disk Model
- Simulations

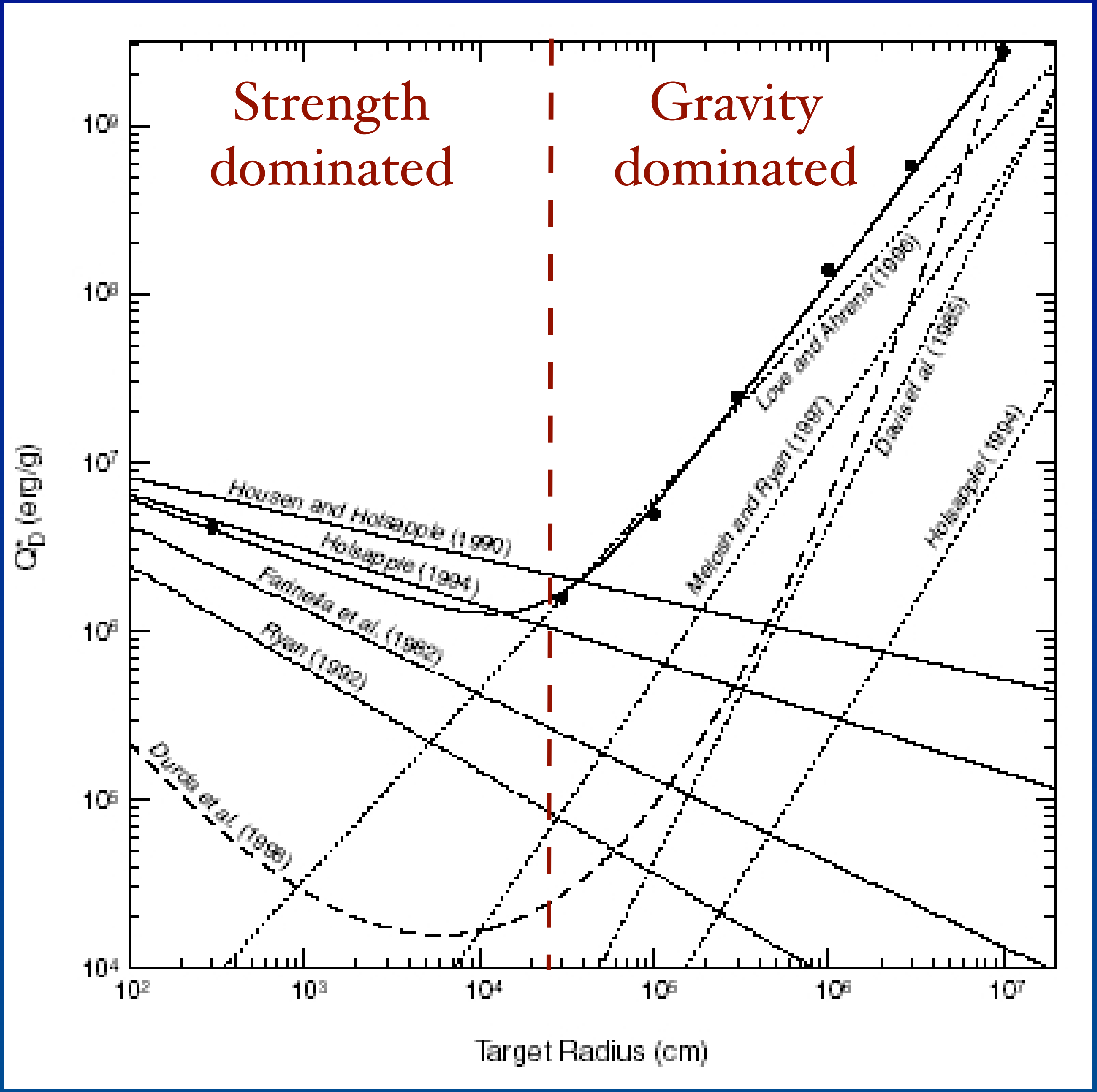
Review of Terrestrial Planet Formation



Our simulations will concentrate on the middle phase

Previous Work on Planet Formation

- Statistical Methods
  - Pros: lots of particles ($N_{max} = 10^8$), gas, fragmentation
  - Cons: assumes homogeneous distribution
- Direct Numerical Simulations
  - Pros: heterogeneous distribution
  - Cons: computationally expensive ($N_{max} = 10^4$)
    Collisions simpilfied: perfect merging (ignores frag.)
    exptrapolated fragmentation law (ignores gravity)

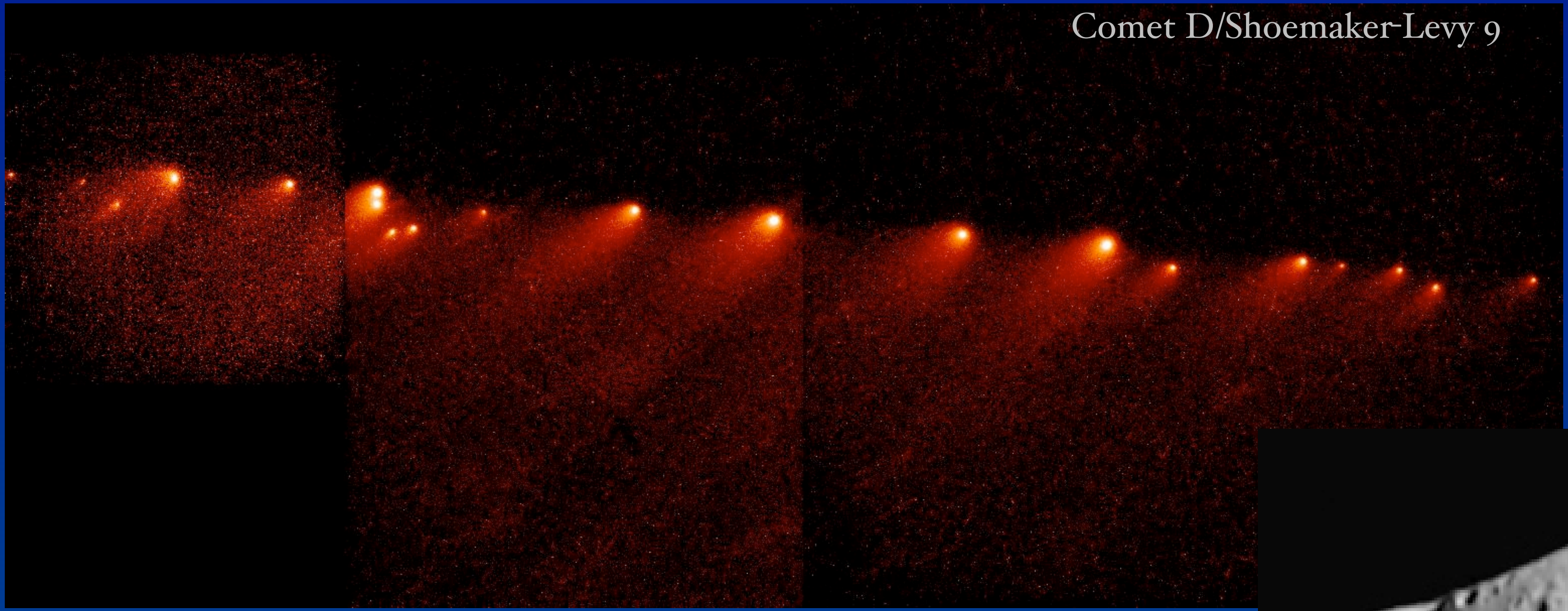


(Asphaug, Ryan, & Zuber 2003)

Method for Terrestrial Planet Simulations

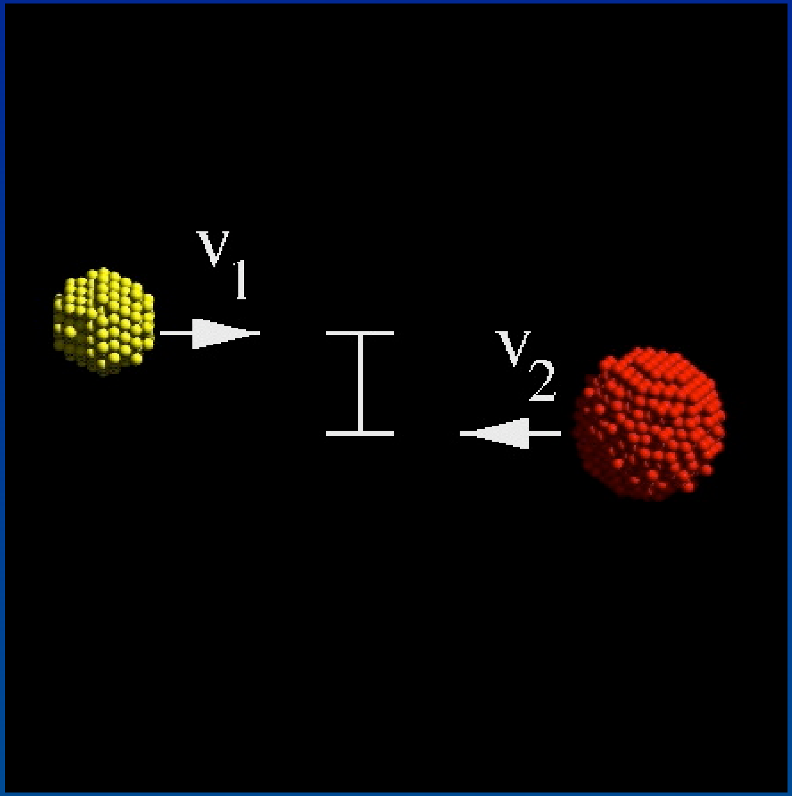
- conduct a series of simulations to investigate affect of environment
- use efficient N-body code pkdgrav
- resolve collisions between planetesimals
- account for dust accretion onto planetesimals
- provide specific characteristics that lead to planets

Planetesimal Structure Model: Rubble-Pile



- Asteroids & Comets: spins, giant craters, low bulk density, tidal disruption
- Objects > 1 km are in the gravity dominated regime

Planetesimal Structure Model: Continued



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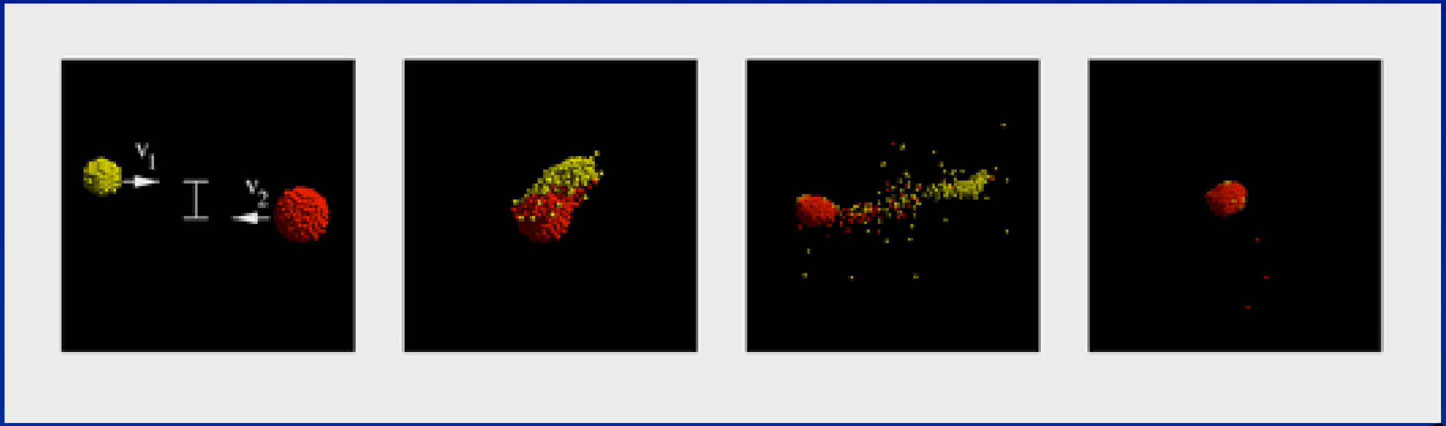
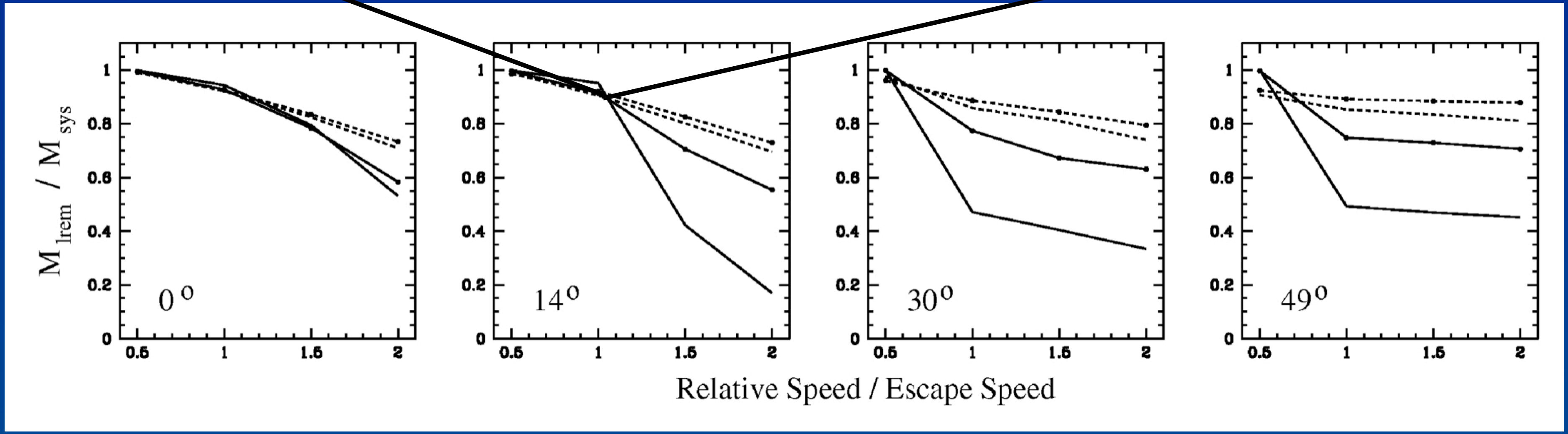
- Rubble piles: fixed number of self-gravitating hard spheres
- Rubble pile particles: no fracturing or merging particles, positions and velocities evolved using pkdgrav under constraints of gravity and physical collisions

Planetesimal Collision

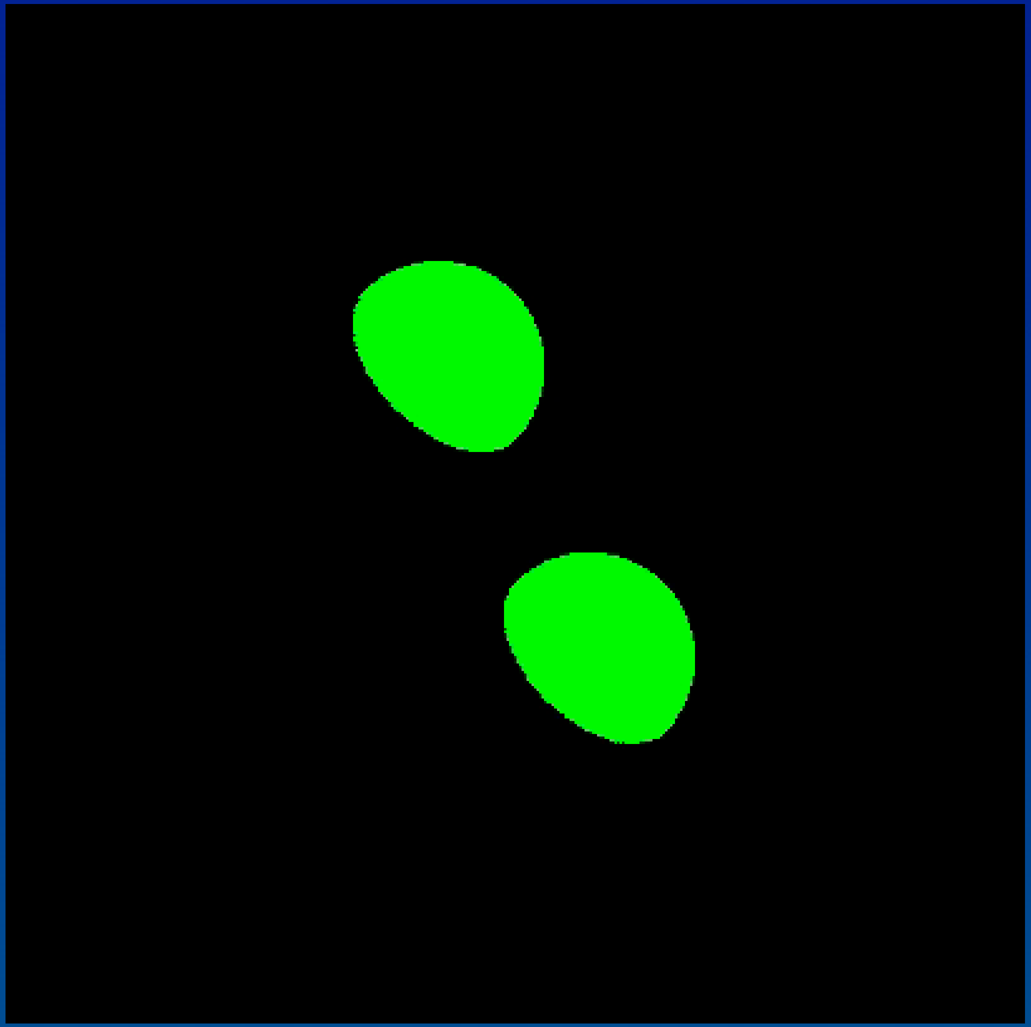




- Outcome Database: relative speed, impact angle, coefficient of restitution, mass ratio

Planetesimal Collision Model: phase II

- Collision Outcome
  - 1 large remnant & “dust” interpolate/extrapolate outcome from database
  - > 1 similar sized remnants directly resolve collisiions



Planetesimal Disk Model

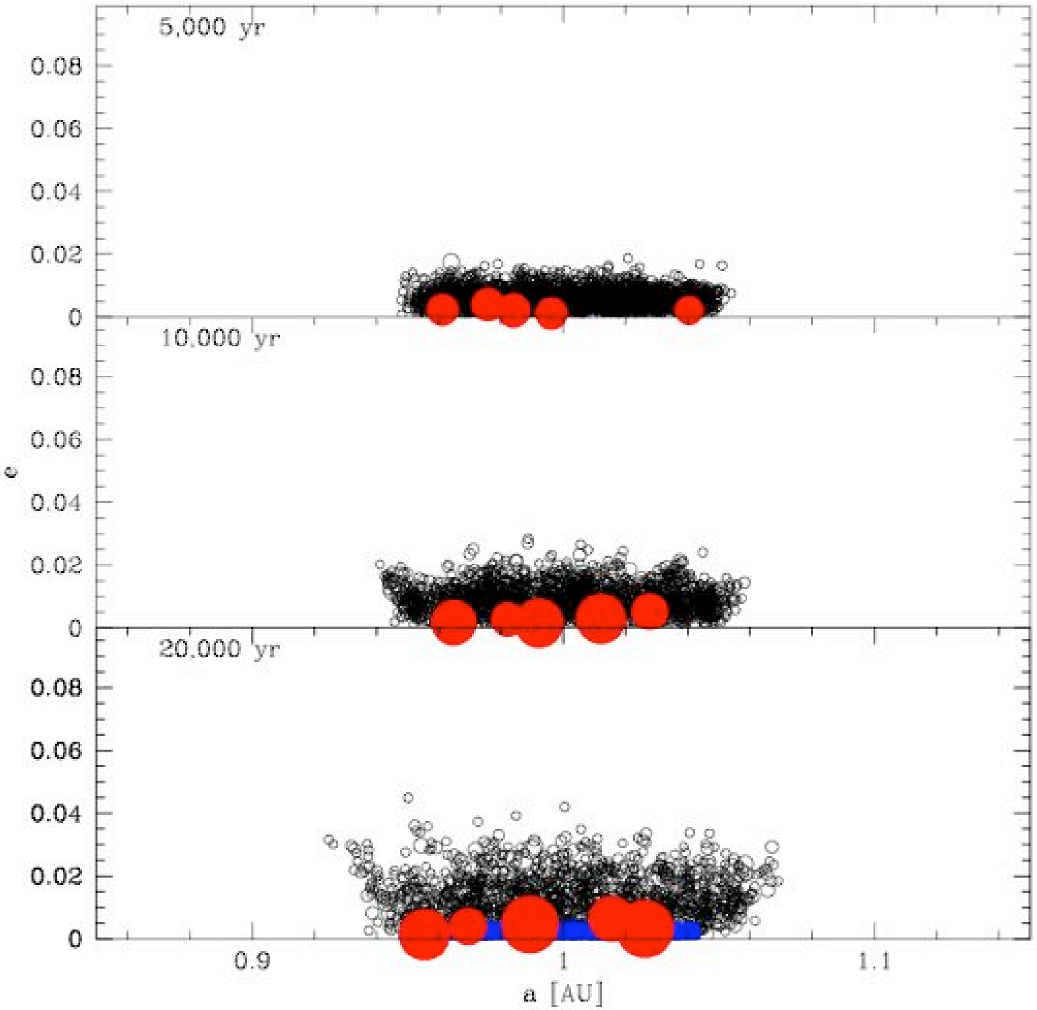
- Resolution Limit: Dust
  - Tracked in radial bins, accreted by planetesimals in that bin
  - $M'_p = M_p + \square m$
    $v'_x = v_{kx} + M_p/M'_p\,(v_x - v_{kx})$; $v'_y = v_{ky} + M_p/M'_p\,(v_y - v_{ky})$
    $v'_z = M_p/M'_p\, v_z$
- N-body Code: pkdgrav
  - parallelized hierarchical tree code (Richardson et al. 2000, Stadel 2001)
  - second order leap frog integrator
  - collision prediction: radius inflated by grav. focusing factor

Simulations

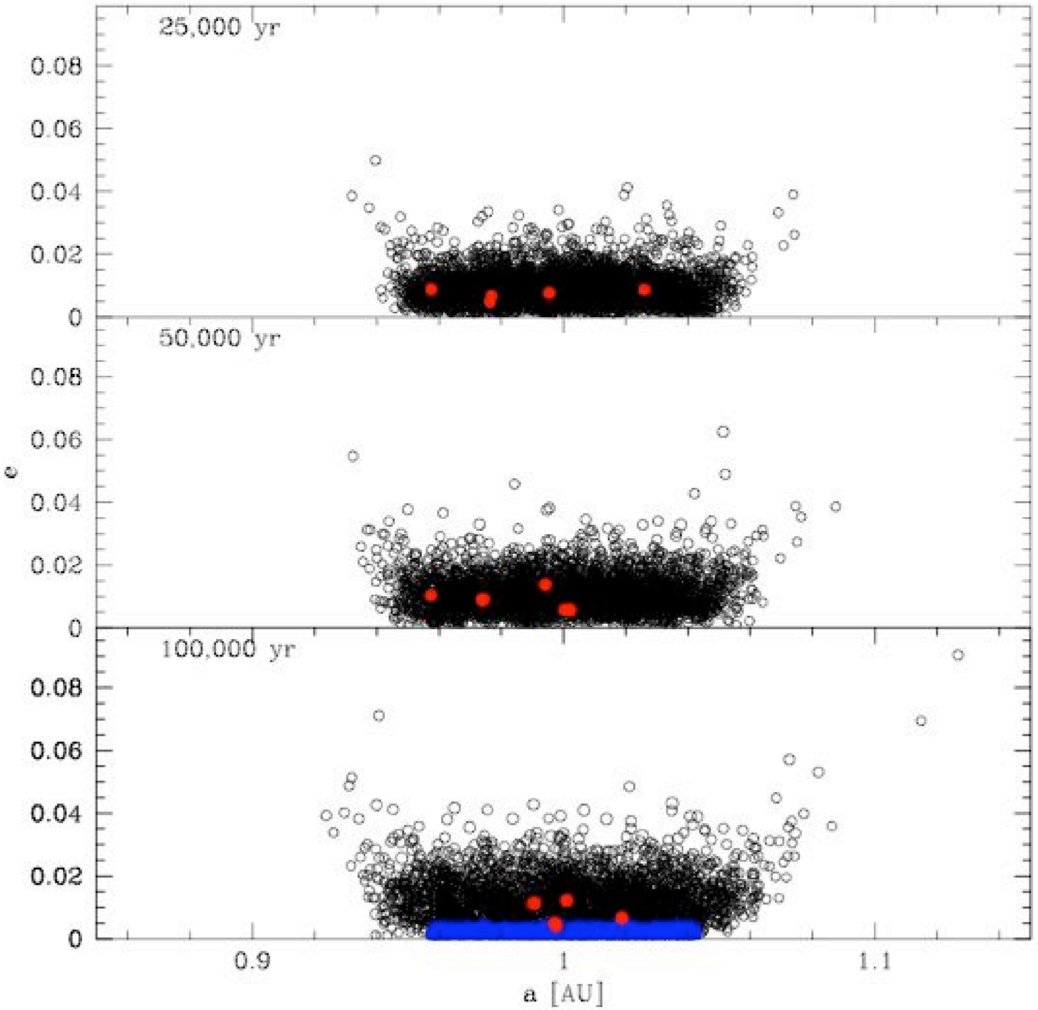
- Test Done !
  - N = 4000, 2 x 10^4 yrs
    $\Sigma_s = \Sigma_1 (a/1\ AU)^{-\alpha}$, da = .085 AU
    Σ_1 = 10 g cm^{-2}; α = 1.5 (Kokubo & Ida 1998, Richardson 2000)
- Effect of environment
  - N = 10^4, 5 x 10^5 yrs Running ...
    Σ_1 = 100, 10, 1 g cm^{-2}; α = 0.5, 1.5, 2.5, da = 1 AU
    (Kokubo & Ida 2002)
  - N = 10^6, 5 x 10^5 yrs, da = 3 AU

Preliminary Results

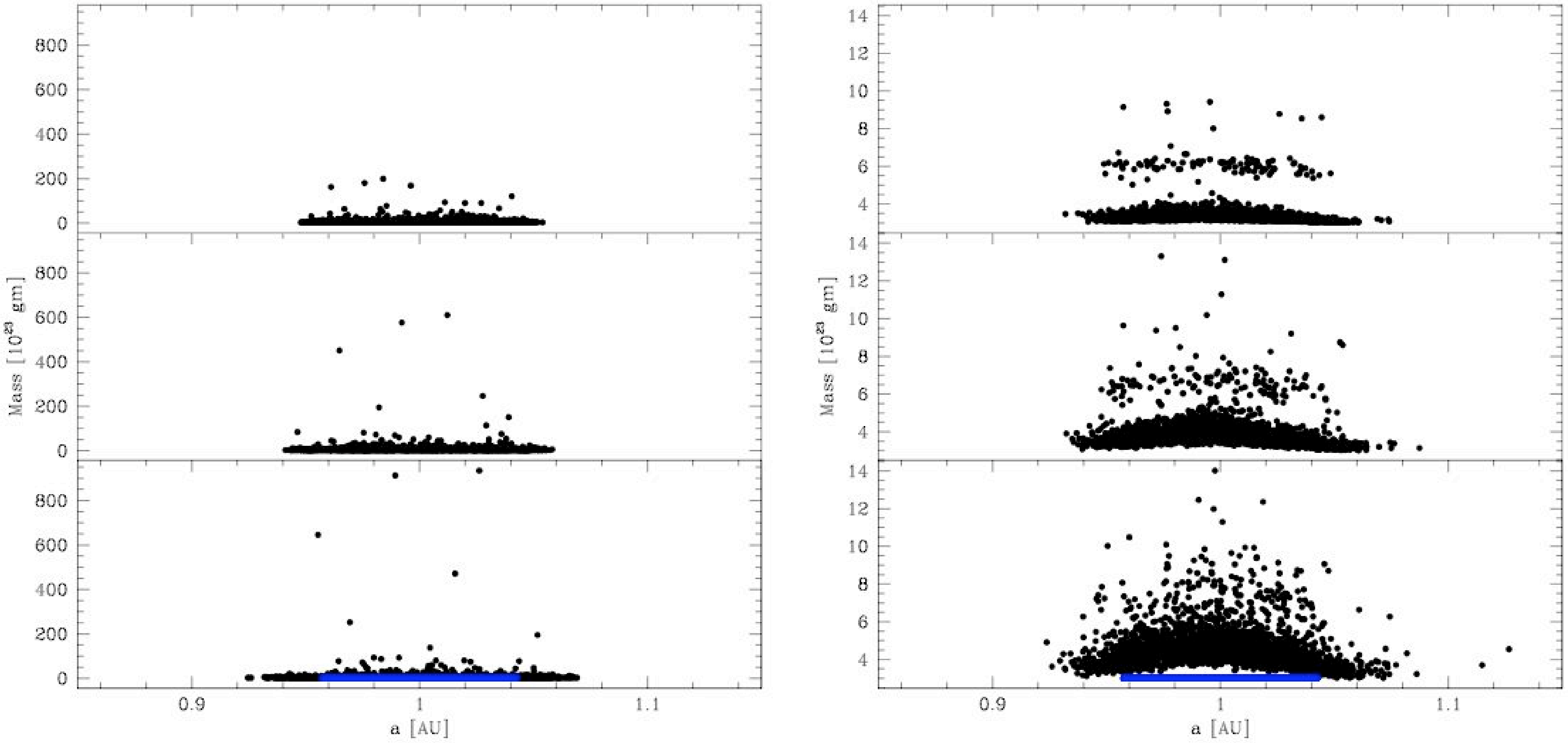
Perfect Merging, f=6



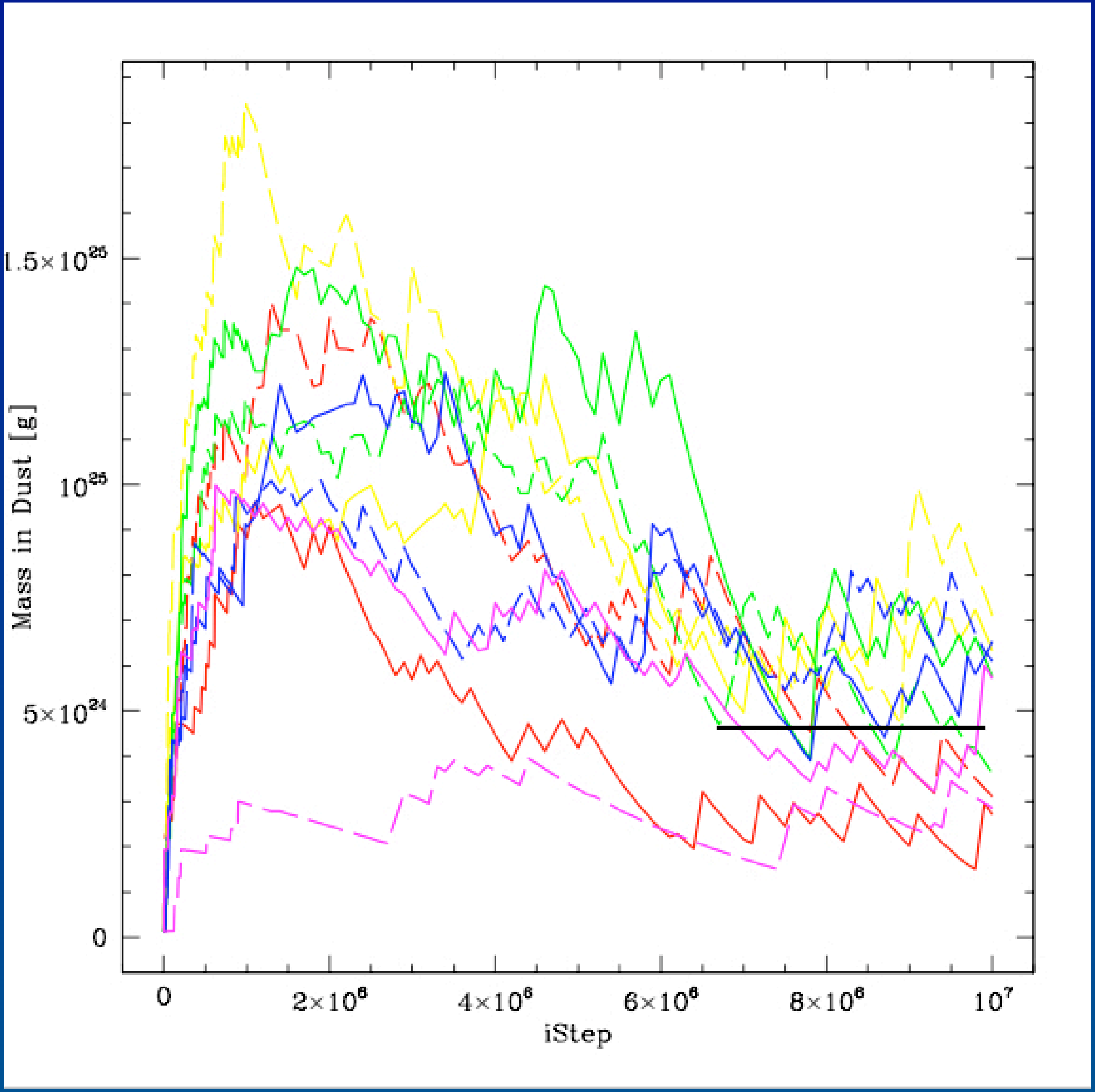
Rubble, f=1



Mass vs Semi-major Axis



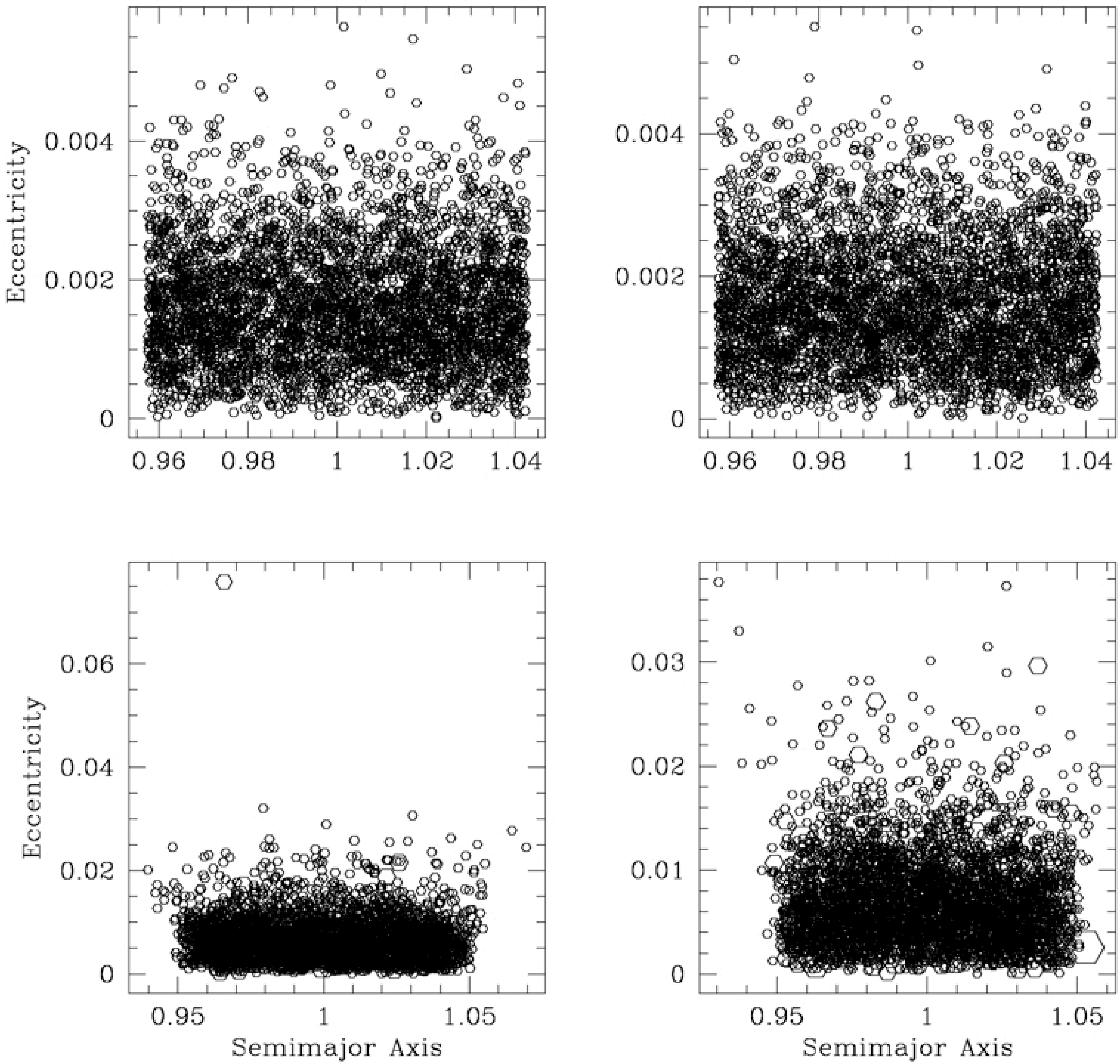
Mass in Small Planetesimals



Initially 1.2e23 g in each bin (.001 x initial mass in particles)
dust reaches equilibrium an order of magnitude higher

Conclusions

- Test understanding of planet formation by including a self-consistent model of fragmentation
- Effect of environment & realistic timescales for terrestrial planet formation
- How easily do Earth-like planets form?



Eccentricity
0.004
0.002
0
0.96
0.98
1
1.02
1.04
0.06
0.04
0.02
0.03
0.01
0.95
1.05
Semimajor Axis