Collisional Dynamics In Planet Formation

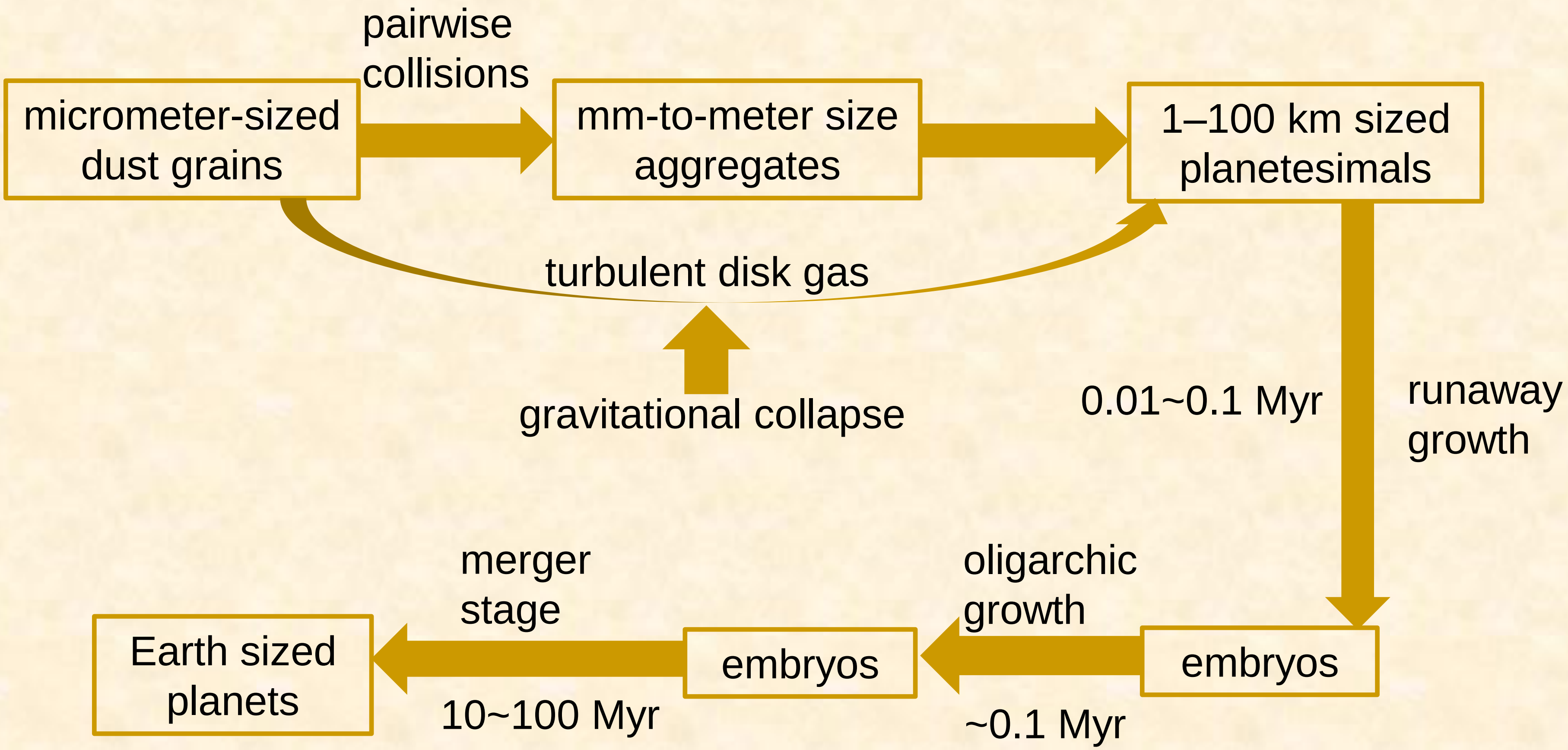
Nan Wang (Nanjing University)

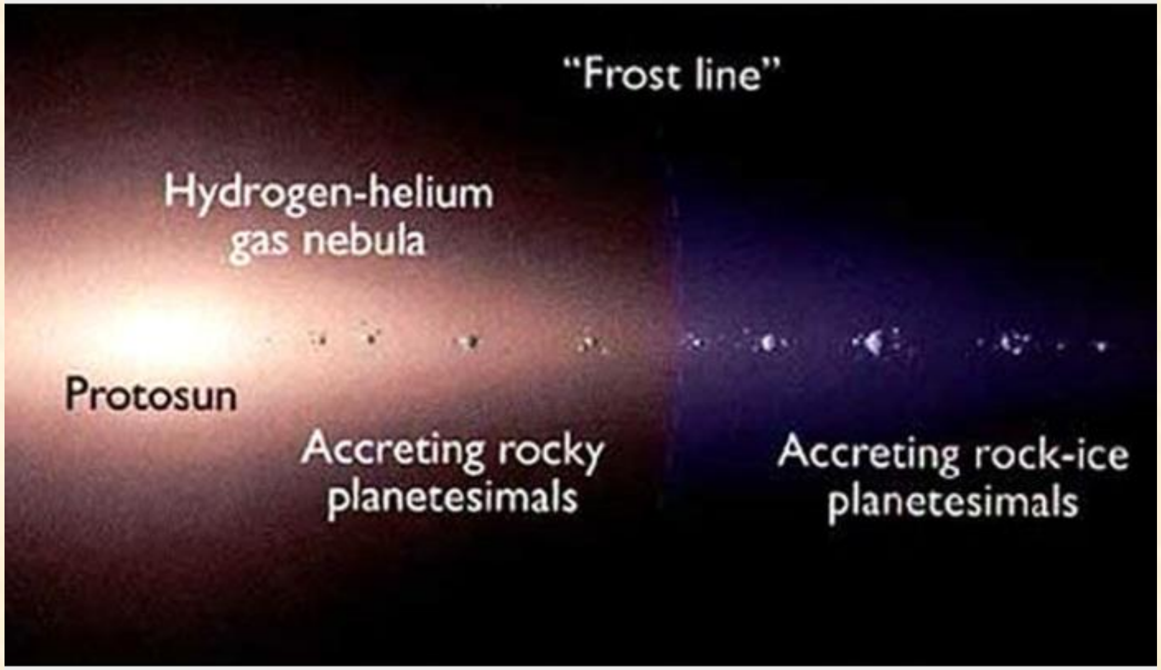
Supervisors: Shang-fei Liu (UCSC)
Diana Valencia (UofT)

Outline

- 1. Terrestrial planet formation
- 2. Collision modeling
- 3. Collision history tracking
- 4. Future work

1. Terrestrial planet formation





The precursors to the planets, called planetesimals, were mostly rocky stuff in the inner solar system within the snow or frost line. The outer planets formed from planetesimals composed mixture of rock and ice. Credit: Univ. of Colorado

Composition of terrestrial planets

Refractory minerals	Si	crust, mantle	pure Si ?
Metals	Fe, Ni	core	pure Fe ?

2. Collision modeling

Collision simulations

- Leinhardt & Stewart (2012)
- Genda et al. (2012)

- Identify the boundaries of different collision regimes
- Fit the mass and speed distributions of fragments

Applications by now

- Kokubo & Genda (2010)
- Chambers (2013)

- Hit-and-run collisions are common.

- High collision rate
- Comparable formation timescale
- Mass reduction of final planets

A specific collision scenario:

M_{targ},	mass of target
M_p,	mass of projectile
R_{targ}	radius of target
R_p,	radius of projectile
b,	impact parameter
V_i,	impact speed

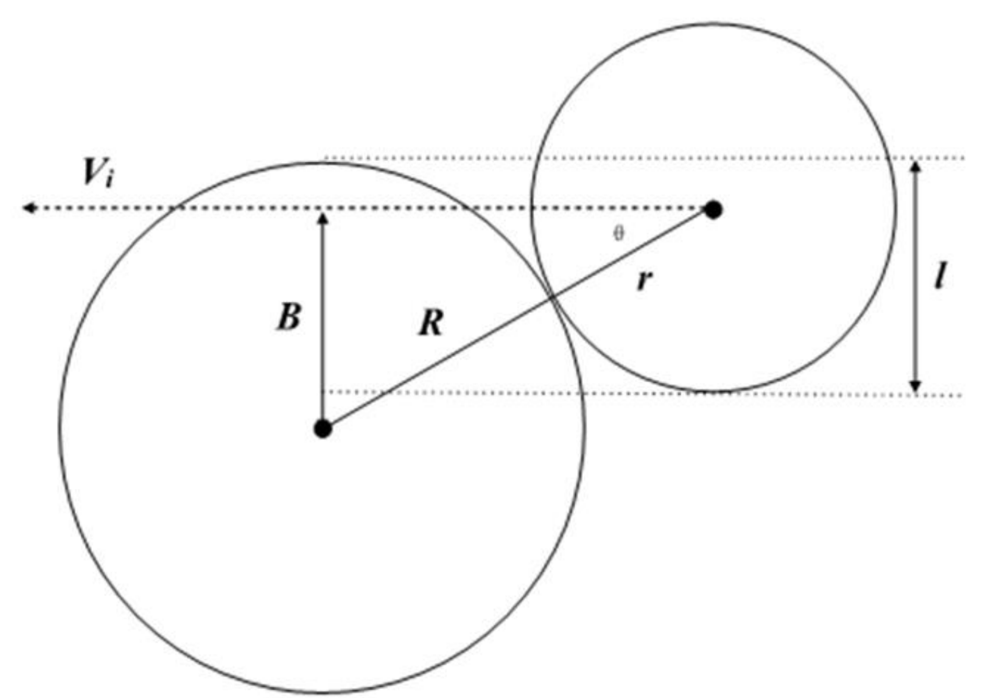


Figure 2. Schematic of the collision geometry. The target is stationary and the projectile is moving from right to left with speed V_i. The impact angle, θ, is defined at the time of first contact as the angle between the line connecting the centers of the two bodies and the normal to the projectile velocity vector. The impact parameter is $b = \sin\theta$.

(Leinhardt and Stewart 2012)

Major Collision Regimes
(Leinhardt & Stewart 2012)

	$b < b_{crit}$	$b > b_{crit}$
$V_i < V'_{esc}$	Merging	
$V'_{esc} < V_i < V_{erosion}$		Hit-and-run
$V_{erosion} < V_i < V_{supercat}$	Disruption	
$V_i > V_{supercat}$	Super-catastrophic Disruption	

Full Accretion

Partial Accretion

Erosion

Non-grazing Impact | Grazing Impact

Major Collision Regimes
(Leinhardt & Stewart 2012)

Disruption

- $0.1 < \frac{M_{lr}}{M_{tot}} < 0.9$
- Linear:
- $M_{lr} \sim Q_R$

Super-catastrophic Disruption

- $\frac{M_{lr}}{M_{tot}} < 0.1$
- Power law:
- $M_{lr} \sim Q_R^{\eta}$

Merging

- $M_{lr} \sim M_{tot}$

Hit-and-run

- $M_{lr} \sim M_{targ}$

Mass of the largest remnant

Disruption:

$$M_{\mathrm{lr}}/M_{\mathrm{tot}} = -0.5(Q_R/Q'^{*}_{\mathrm{RD}} - 1) + 0.5. \qquad (5)$$

Super-catastrophic disruption:

$$M_{\mathrm{lr}}/M_{\mathrm{tot}} = \frac{0.1}{1.8^{\eta}}(Q_R/Q'^{*}_{\mathrm{RD}})^{\eta}, \qquad (44)$$

where

$$Q_R = \left(0.5 M_{\mathrm{p}} V_{\mathrm{p}}^2 + 0.5 M_{\mathrm{targ}} V_{\mathrm{targ}}^2\right)/M_{\mathrm{tot}},$$
$$= 0.5 \mu V_i^2 / M_{\mathrm{tot}}, \qquad (1)$$

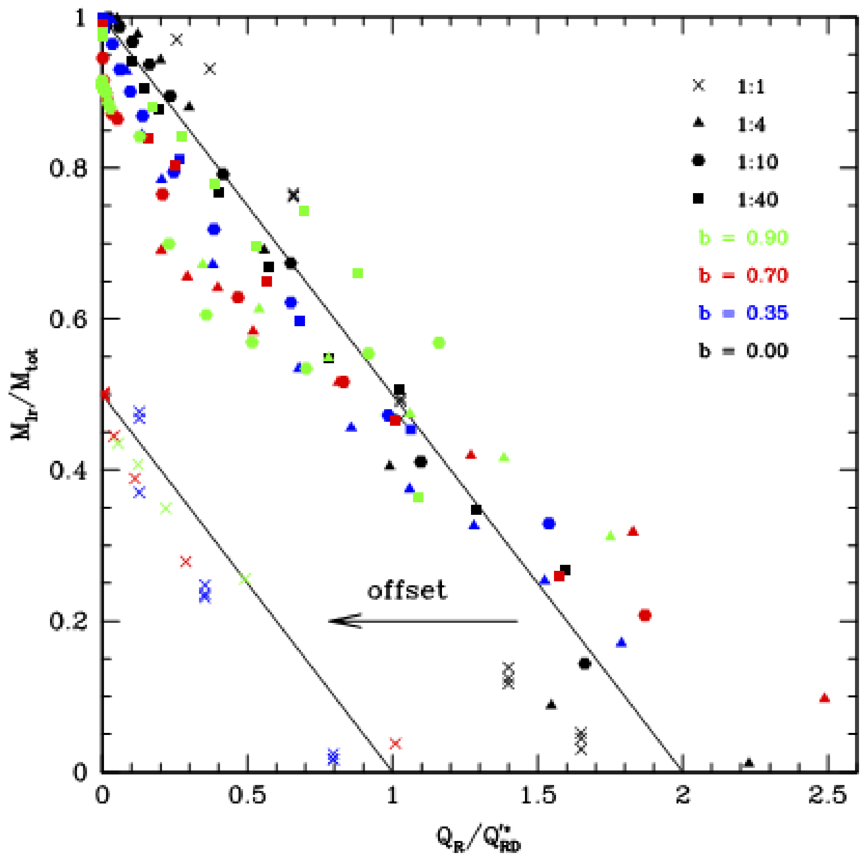


Figure 3. Normalized mass of the largest post-collision remnant vs. normalized impact energy for all collisions in the disruption regime. The impact energy is scaled by the empirical catastrophic disruption criteria Q'^{*}_{RD} (Table 1). The solid lines are the universal law for the mass of the largest remnant (Equation (4)); see the text for discussion of 1:1 oblique impacts. The symbol denotes the projectile-to-target mass ratio, and the color denotes the impact parameter.

(Leinhardt and Stewart 2012)

Velocity of the largest remnant

Assumptions:

$b > 0.7$: $V_{lr} \sim V_{targ}$

$b = 0$: $V_{lr} \sim V_C = 0$

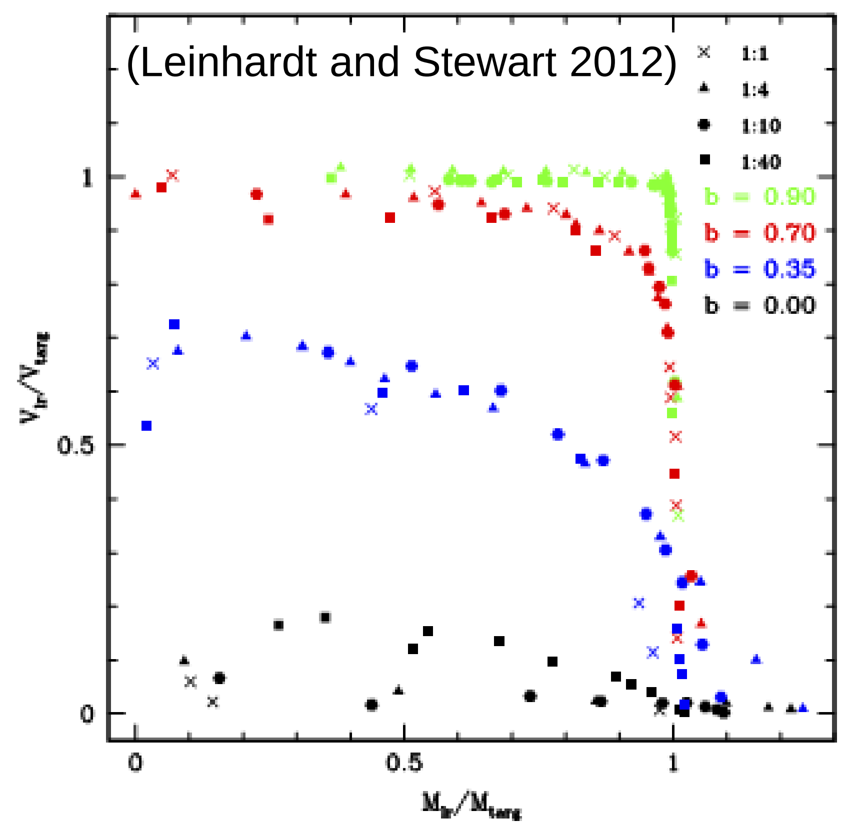


Figure 6. Velocity of largest remnant with respect to the initial center of mass target velocity vs. the mass of largest remnant normalized by the mass of the target. Impact angle is indicated by color; mass ratio is indicated by symbol.

(A color version of this figure is available in the online journal.)

Derivation:

	$0 \le b \le 0.7$	$b > 0.7$
$\frac{M_{lr}}{M_{targ}} \le 1$	$\frac{V_{targ}}{0.7} b$	V_{targ}
$1 < \frac{M_{lr}}{M_{targ}} \le 1 + \gamma$	$\frac{V_{targ} b}{0.7\gamma} [-\frac{M_{lr}}{M_{targ}} + (\gamma + 1)]$	$\frac{V_{targ}}{\gamma} [-\frac{M_{lr}}{M_{targ}} + (\gamma + 1)]$

Masses of fragments

n(D): number of objects with radii between D and D+dD.

$$n(D)dD = CD^{-(\beta+1)}dD, \qquad (31)$$

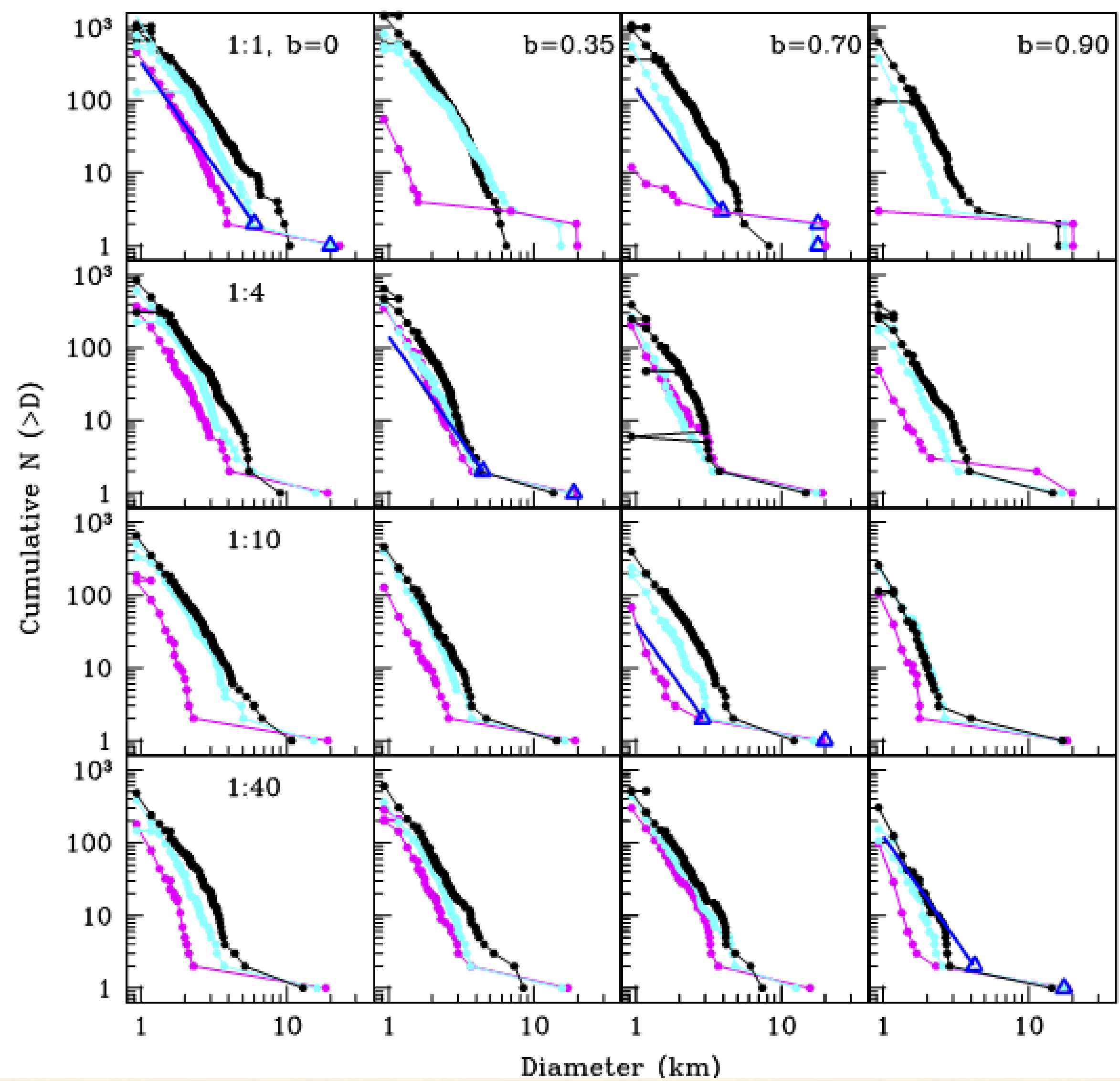
Derivation:

Mass between D and D+dD:

$$dM = n(D)\cdot\frac{4}{3}\pi\rho D^3 dD$$

Radius-binned mass:

$$M(D_l, D_u) = \frac{4}{3}\pi\rho C\frac{D_u^{3-\beta} - D_l^{3-\beta}}{3-\beta}$$



(Leinhardt and Stewart 2012)

Velocities of fragments

dm: total mass of fragments with speeds between v and v+dv.

$$\log\left(\Delta v \frac{dm}{dv}\right) = (A - Sv), \qquad (39)$$

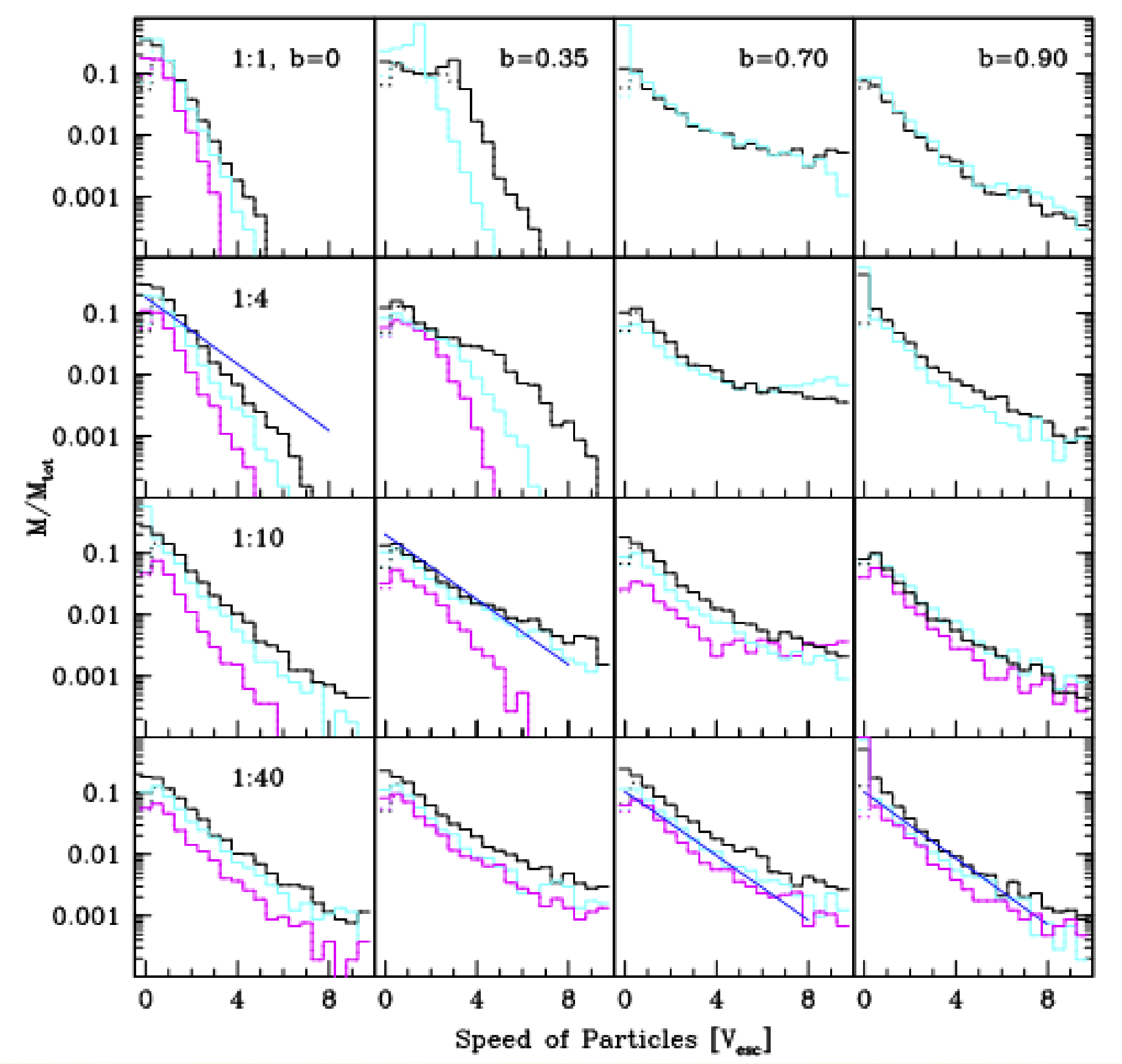
Derivation:

Velocity-binned mass:

$$m(v_l, v_u) = \frac{10^{A-Sv_l} - 10^{A-Sv_u}}{S(ln10)\Delta v}$$

where

$$m = \frac{M}{M_{tot}}, \qquad v = \frac{V}{V_{esc}}$$



(Leinhardt and Stewart 2012)

3. Collision history tracking

Particle identifiers:

ID0 — ID of itself

ID1, ID2 — ID of its parents

ID3 =

0	merger
1	fragment from ID1
2	fragment from ID2
-1	initial body

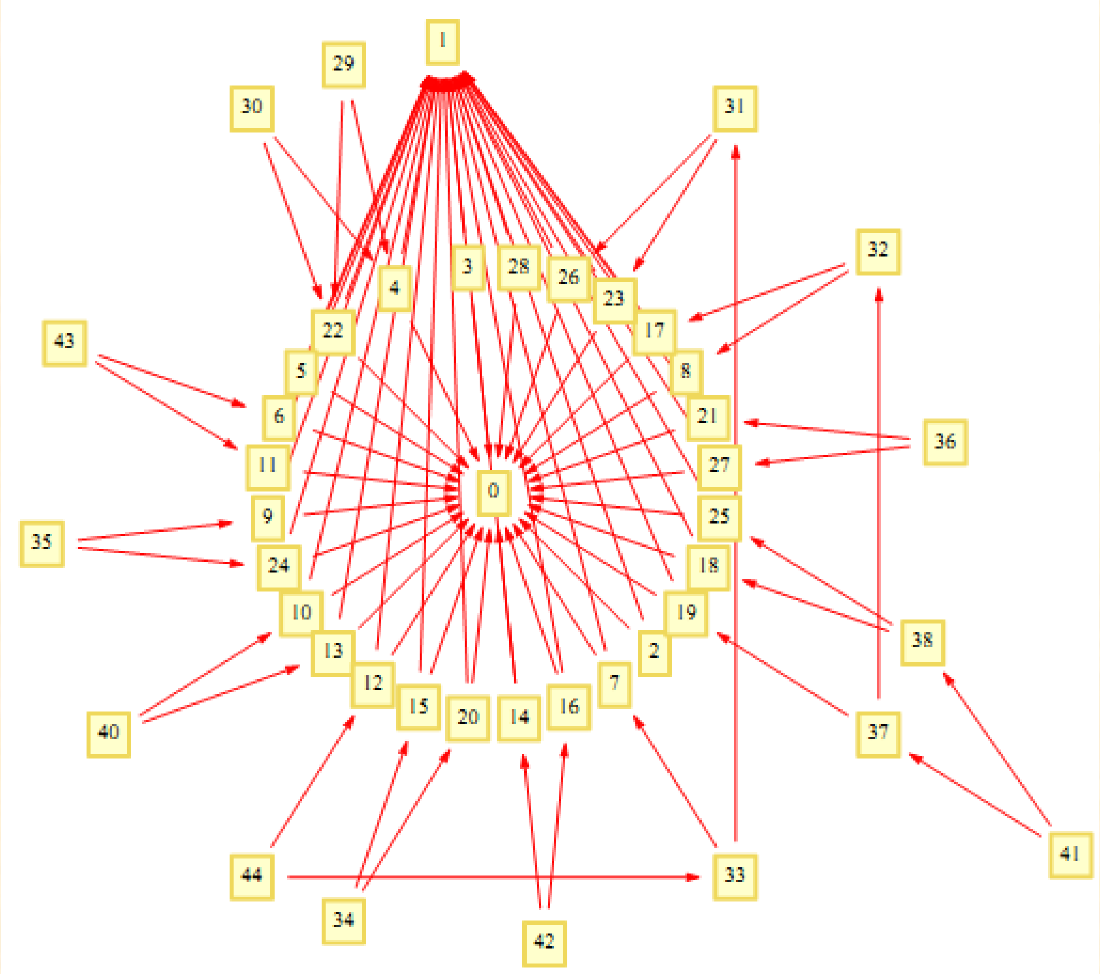
A tentative case

Initialization:

2 bodies with equal masses

Collision model:

Fragmentation + Coagulation (Chambers 2013)



4. Future Work

- Distributed masses of fragments
- Simulations in collision model:
  - 14 Mars-sized embryos + 140 Lunar-sized planetesimals + Jupiter & Saturn

- Results:
  - Structure of final planet system
  - Timescale of formation
  - Compositions of terrestrial planets
  - Comparison with merger model
  - …