Forming Protoplanets from Planetesimals:
The collisional evolution of planetary building blocks

Zoë Malka Leinhardt
Department of Applied Mathematics and Theoretical Physics, University of Cambridge
Department of Physics, University of Bristol

Outline

The Context

a. Observational Constraints - extrasolar planets, the solar system
b. Planet Formation Story - “Once upon a time there was a cloud of gas ...”
c. The Unknowns - planetesimal formation mechanism, initial conditions

Planetesimal Collisions

a. Catastrophic Disruption Threshold - accretion or erosion?
b. Velocity Dependent Collisional Response
c. In Future - scaling laws

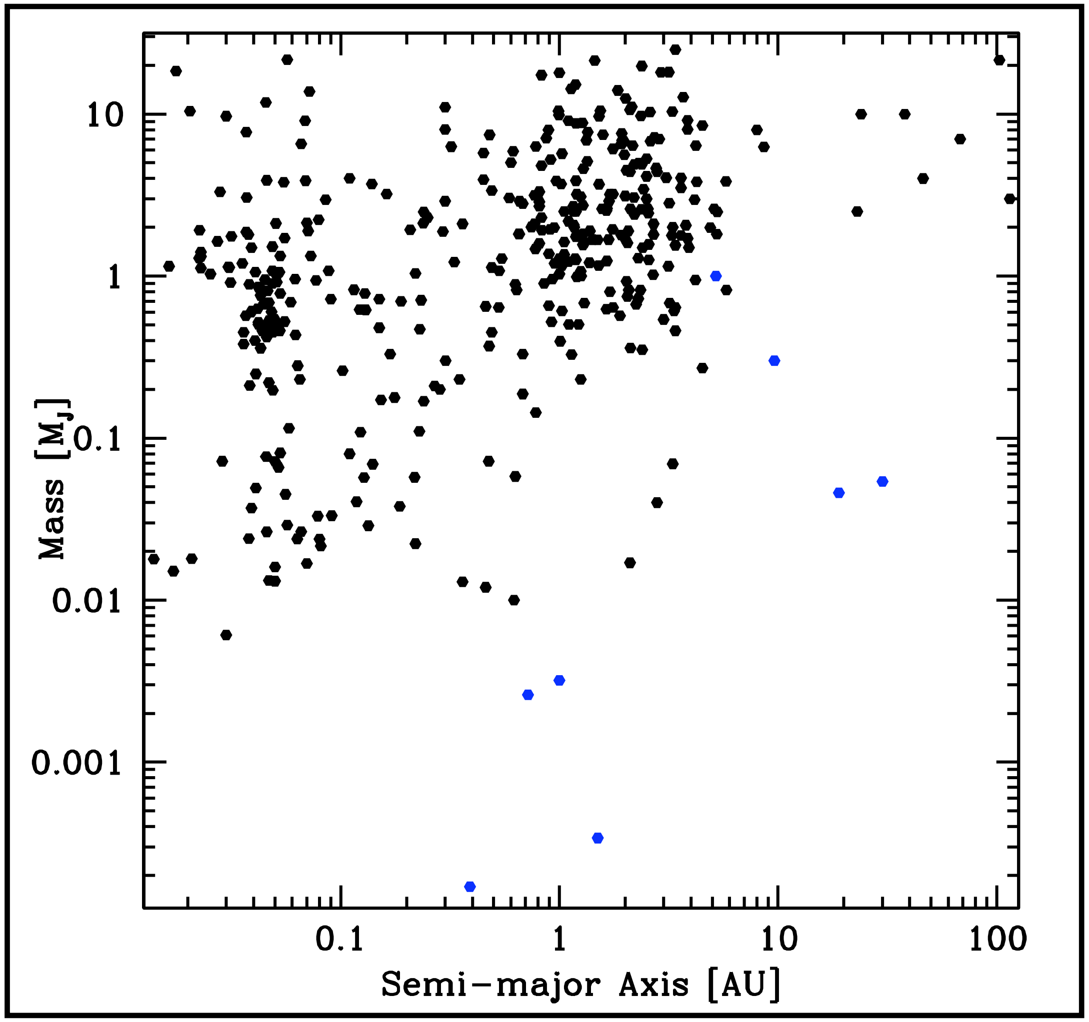
One Collisional Event in Detail (Haumea Family)

a. Analytic determination of collisional regime
b. Numerical confirmation

Discussion

a. What does this all mean for planet formation?

Observational Constraints: Exoplanets



Data from exoplanet catalog (http://exoplanet.eu/catalog.php)

- 464 planets outside our Solar System (29/06/10)
- Diverse: 68 hot Jupiters, 21 Super-Earths, 45 multiple systems, 69 around low mass stars (K & M), 4 around pulsars
- No exoplanet systems similar to the Solar System (yet)
- Planet formation is common: 5% of Sun-like stars have a Jupiter-mass planet (Marcy & Butler, 2000), 30% have a super-Earth (Lovis et al. 2009)

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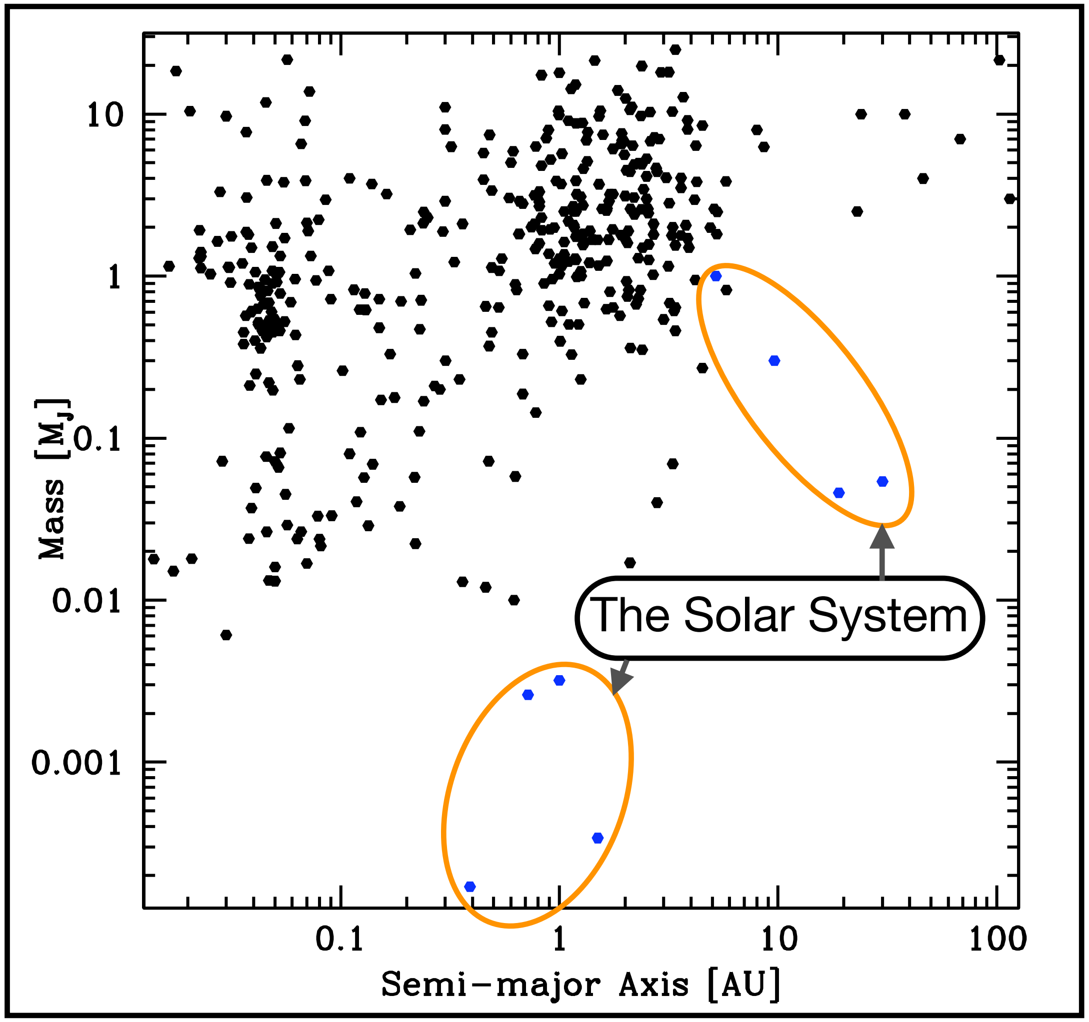

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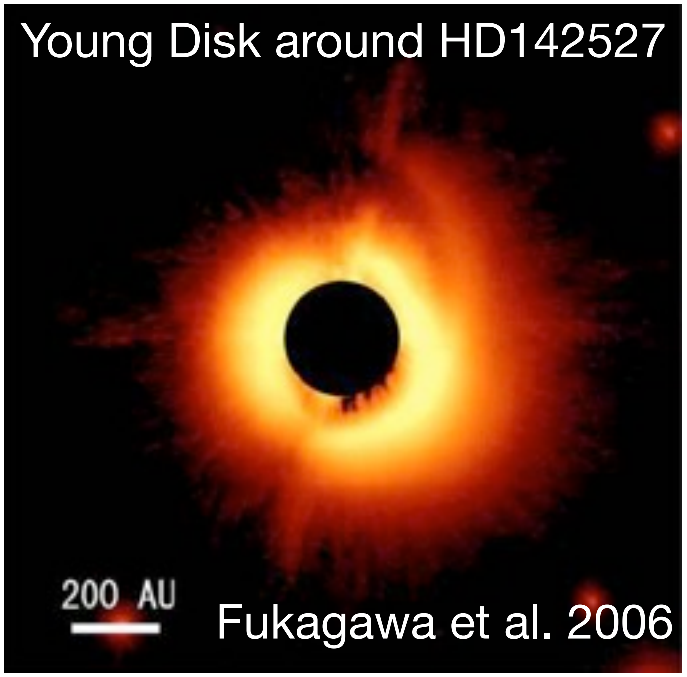
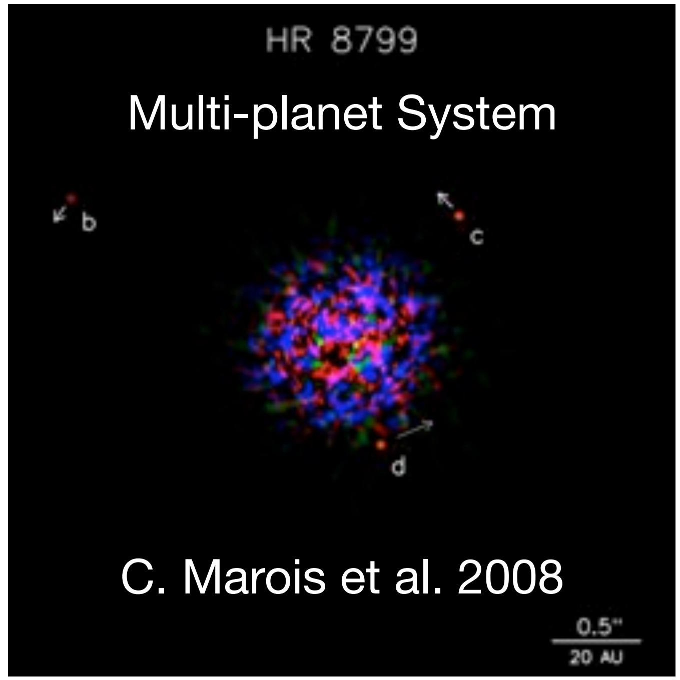
The Problem

- Observations provide snapshots of early and late stages but cannot trace full history of planet formation

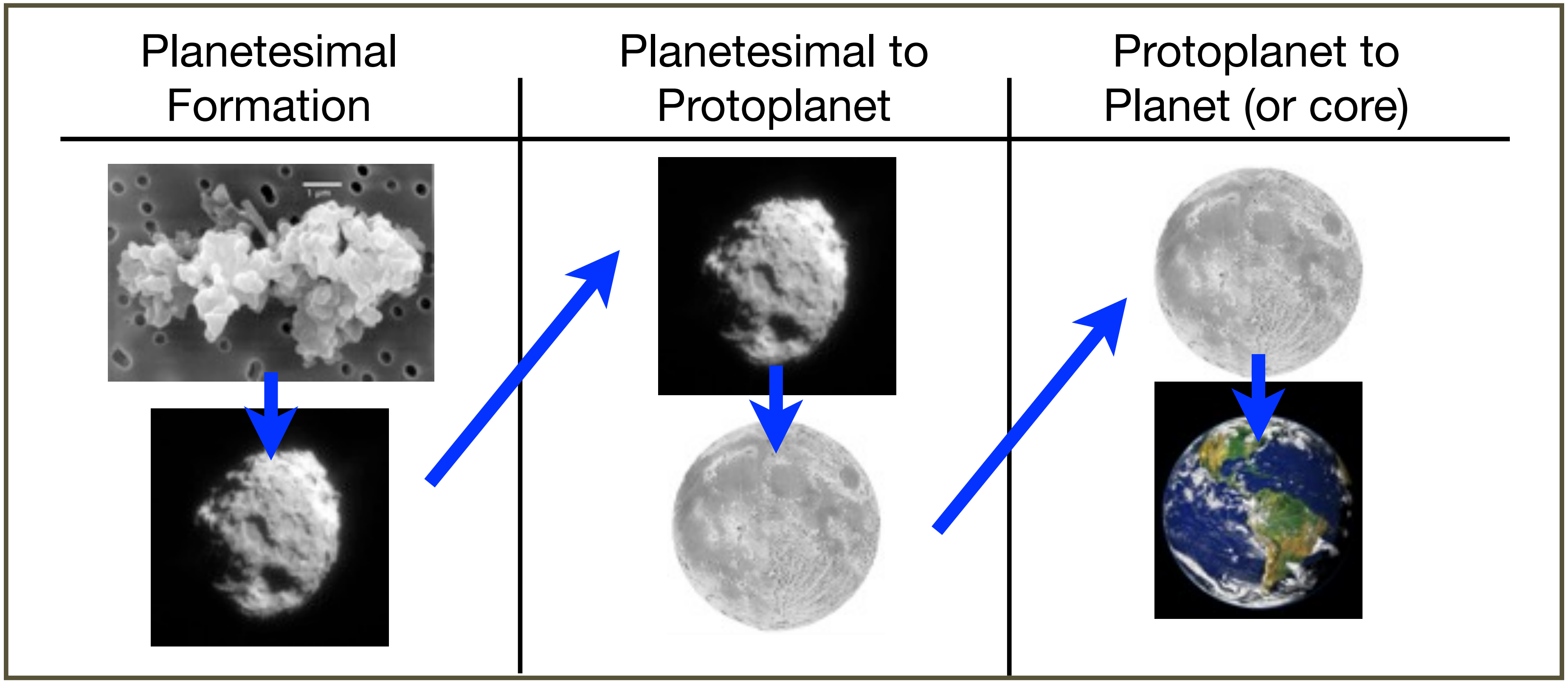




- No existing complete numerical model of planet formation that can connect early and late stages due to numerical limitations and incomplete physical models

Idealized Story: Planetesimal Theory

Planetesimal theory described by “isolated” phases - influence from the previous phase by its end state only



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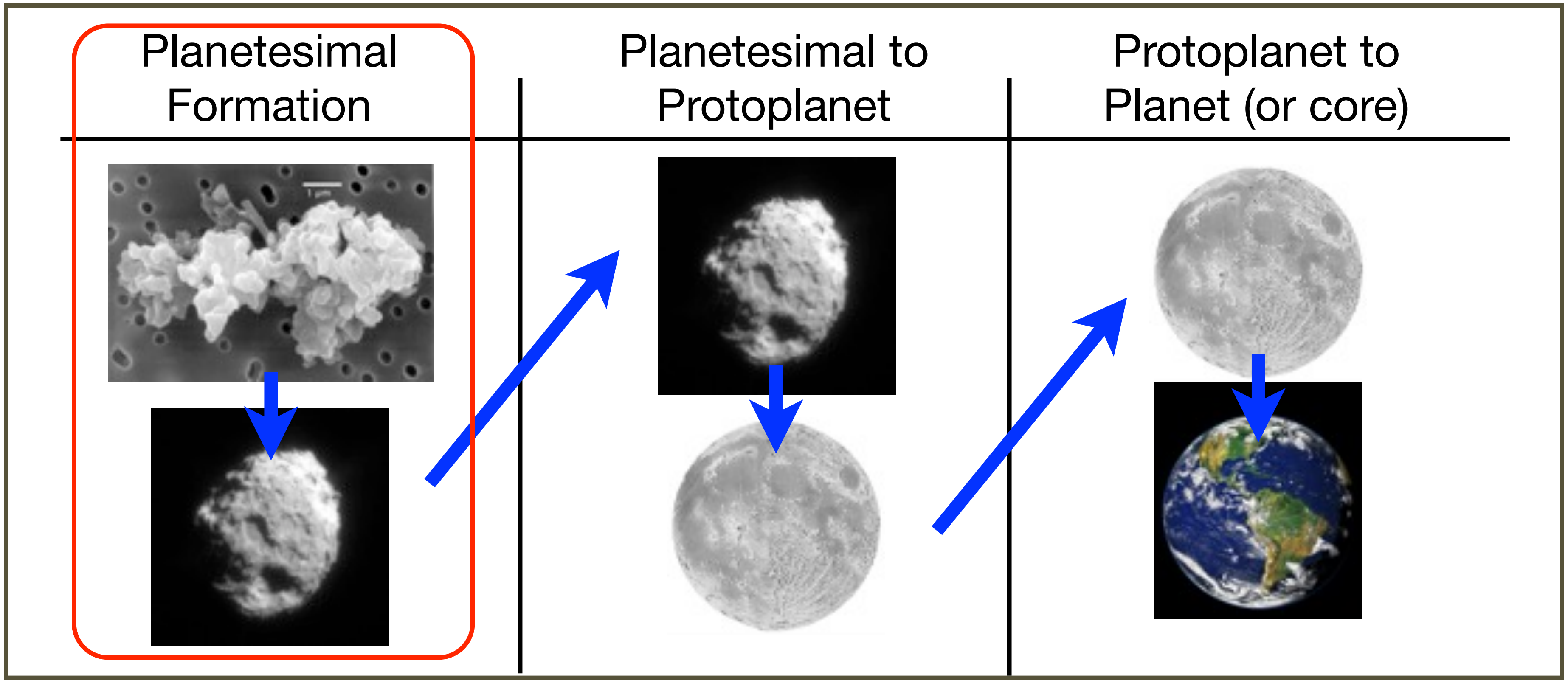

Planetesimal Formation: Hypotheses

- **Coagulation**: growth accretion dominated collisions of dust
  pro: consistent with meteorites
  con: typical velocity dispersion is too fast (Blum & Wurm 2008)
  slow - meter-size will spiral into sun before decoupling from gas
  (Weidenschilling 1977)
  weak - km-sized very fragile could be ground down by collisions
  (Leinhardt & Stewart 2009, Stewart & Leinhardt 2009)

- **Gravitational Instability**: collapse of dust layer (Goldreich & Ward 1973)
  pro: fast - avoids intermediate sizes
  con: turbulence heats up the dust layer reducing the density
  solutions: turbulence at small scales (Cuzzi et al 2008)
  turbulence + streaming instability (Johansen et al 2007)

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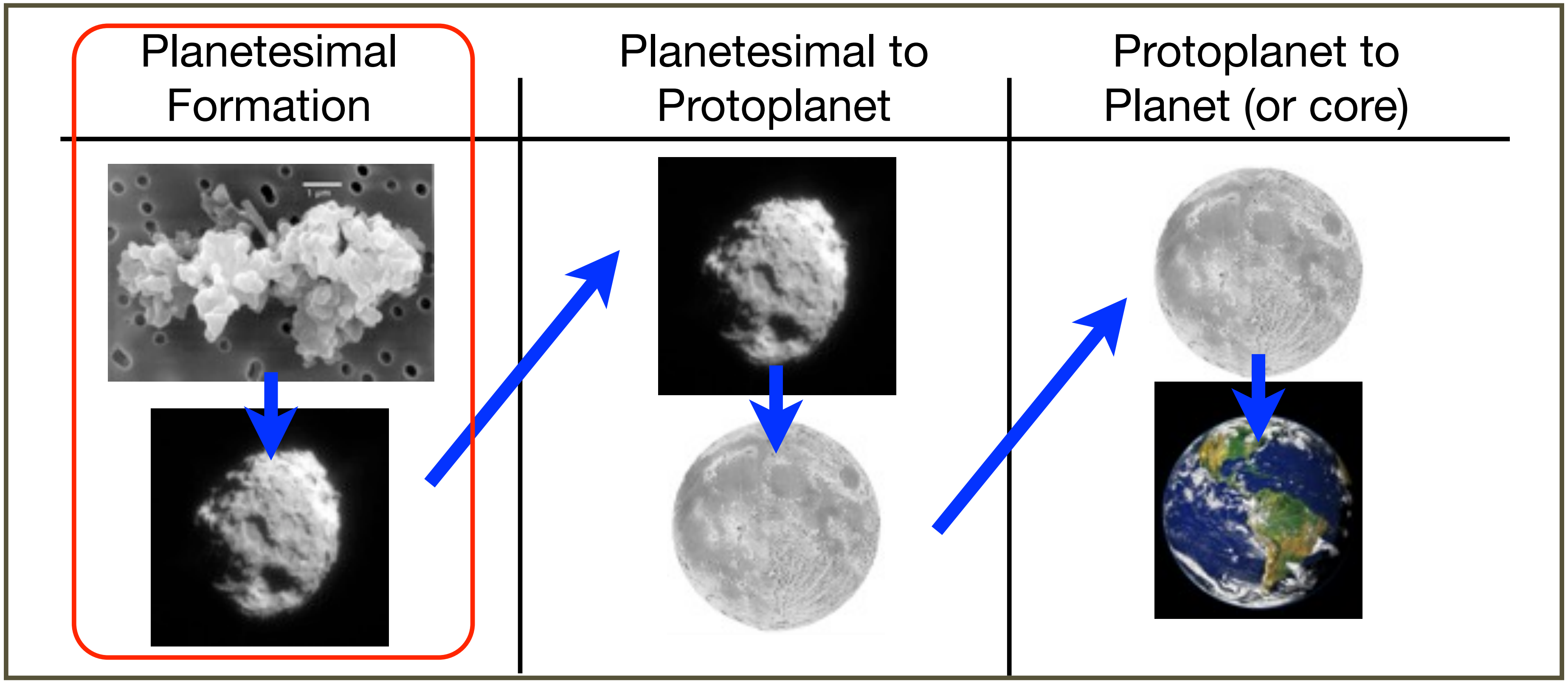

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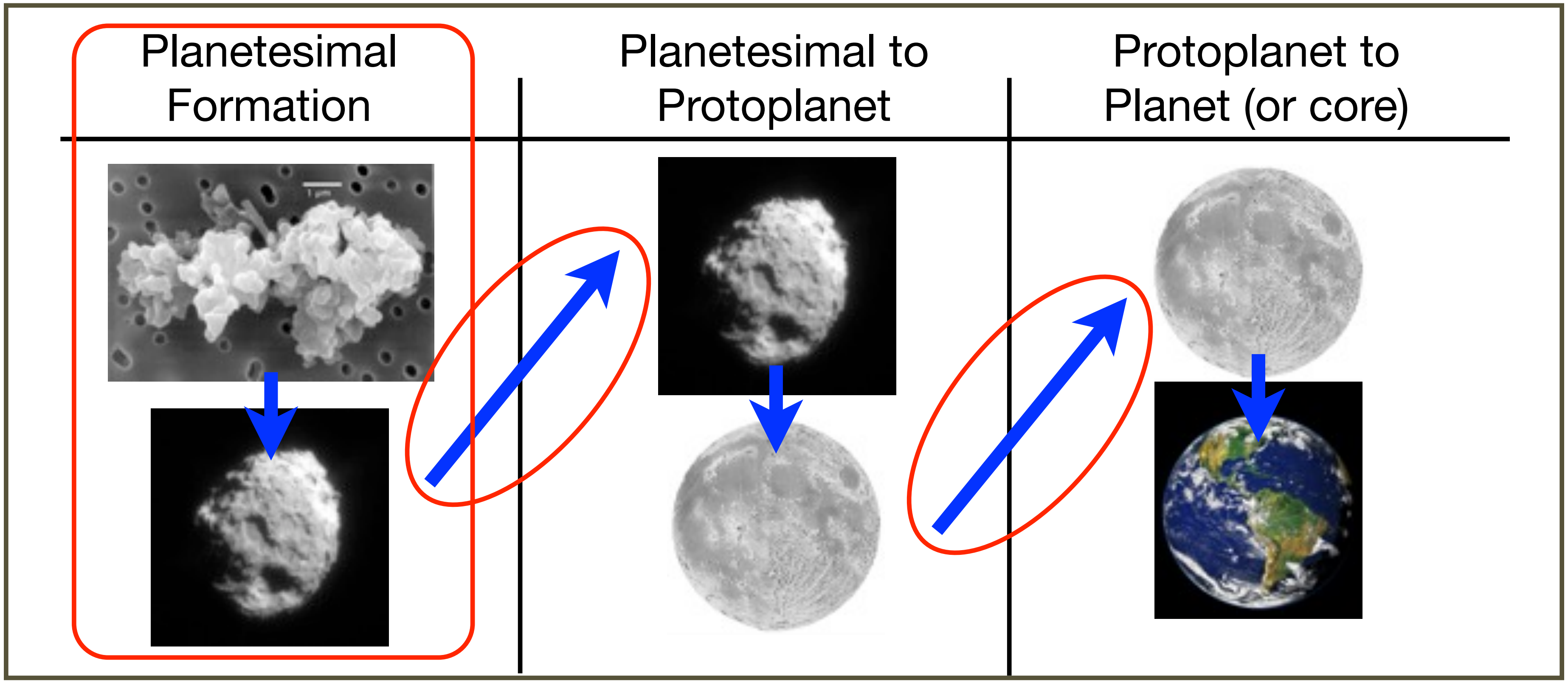
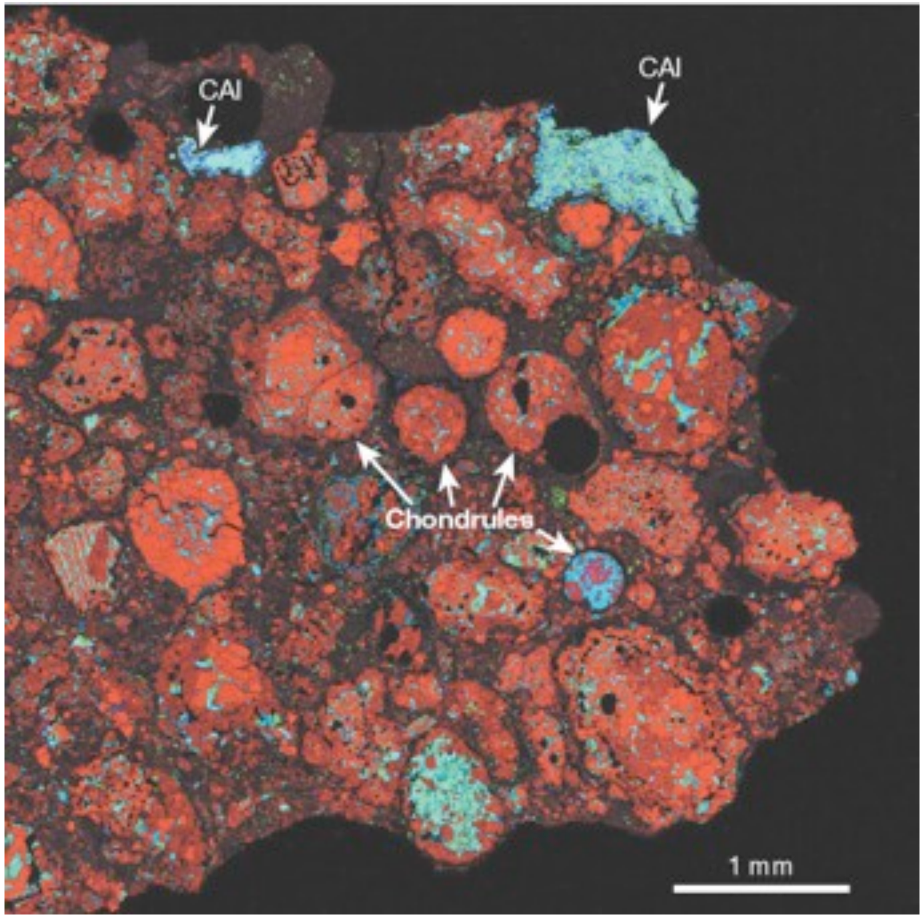


Isolation of phases is a simplification - phases should interact & overlap

Multiple Generations: the Solar System

- Planetesimal formation occurs over long timescale (Hf/W chronology, Kleine 2009): differentiated planetesimals (iron meteorites) formed quickly after CAI + 1 Myr, ordinary chondrites (undifferentiated planetesimal) formed at least 1 Myr later.

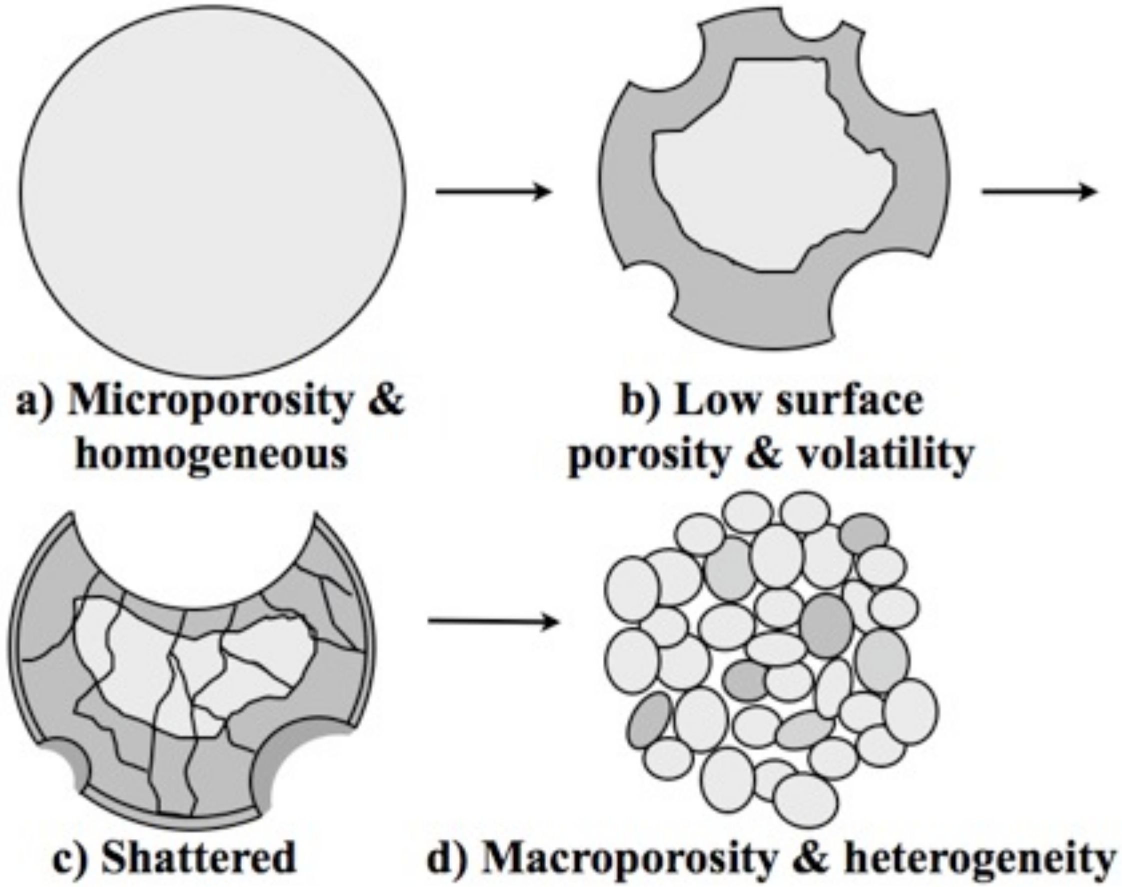
- Chondrites formed slowly: Calcium aluminium rich inclusions (CAIs) oldest solar system material (4.56 Gyr), chondrules younger > 1 Myr find both in the same meteorite



X-ray cross section of meteorite PCA 91082, chondrules in red (Mg), CAIs in blue (Al), Image from Krot Univ. of Hawaii

Planetesimal Evolution

- **Planetesimal composition**: changes with time and distance from sun - initially porous planetesimals compact (& melt) into solid planetesimals. Solid planetesimal may be disrupted into rubble piles.
- **Impact speed**: increases from subsonic to supersonic as solar system evolves
- **Q_D***: will change during planet formation



Leinhardt et al. 2008

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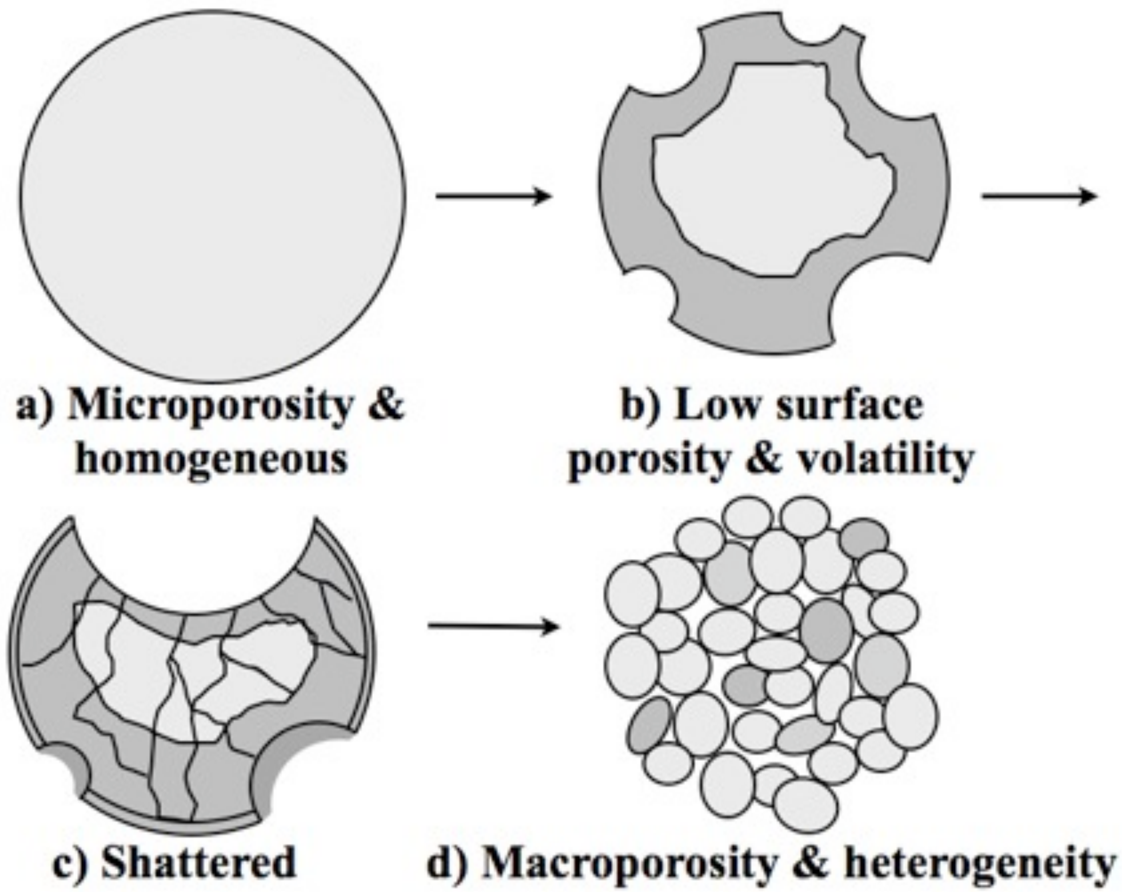
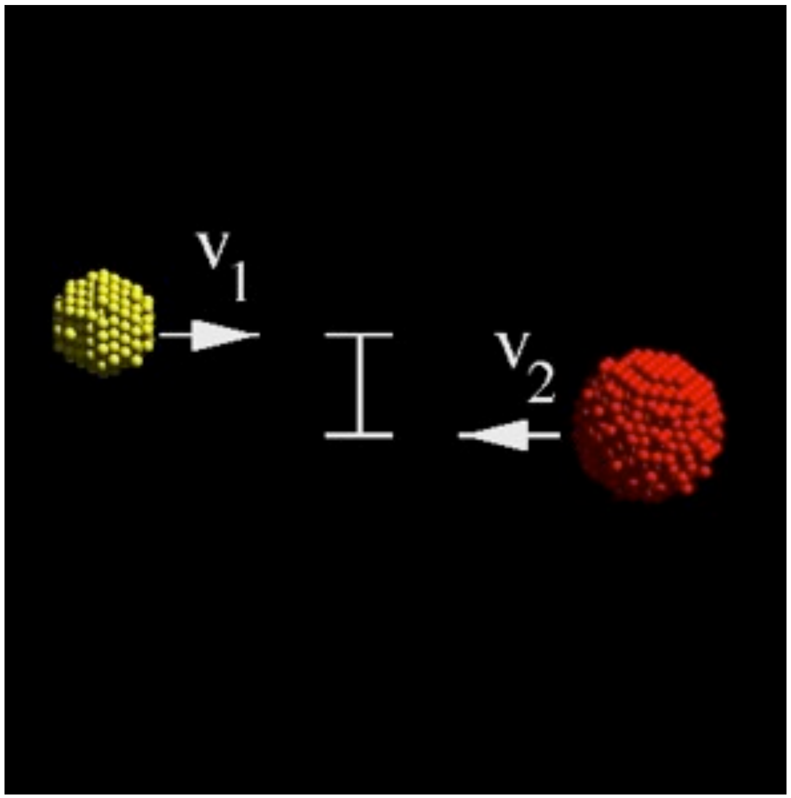


Leinhardt et al. 2008

Numerical Method for Subsonic Collisions



- Modelled with N-body code **`pkdgrav`**
- Target and projectile are gravitational aggregates, similar mass & ρ = 0.5 - 3.0 g/cm^3
- Rubble-pile particles cannot fracture, only gravity and collisions (no cohesion)
- Inelastic collisions between particles governed by ε_n = 0.2 - 0.8

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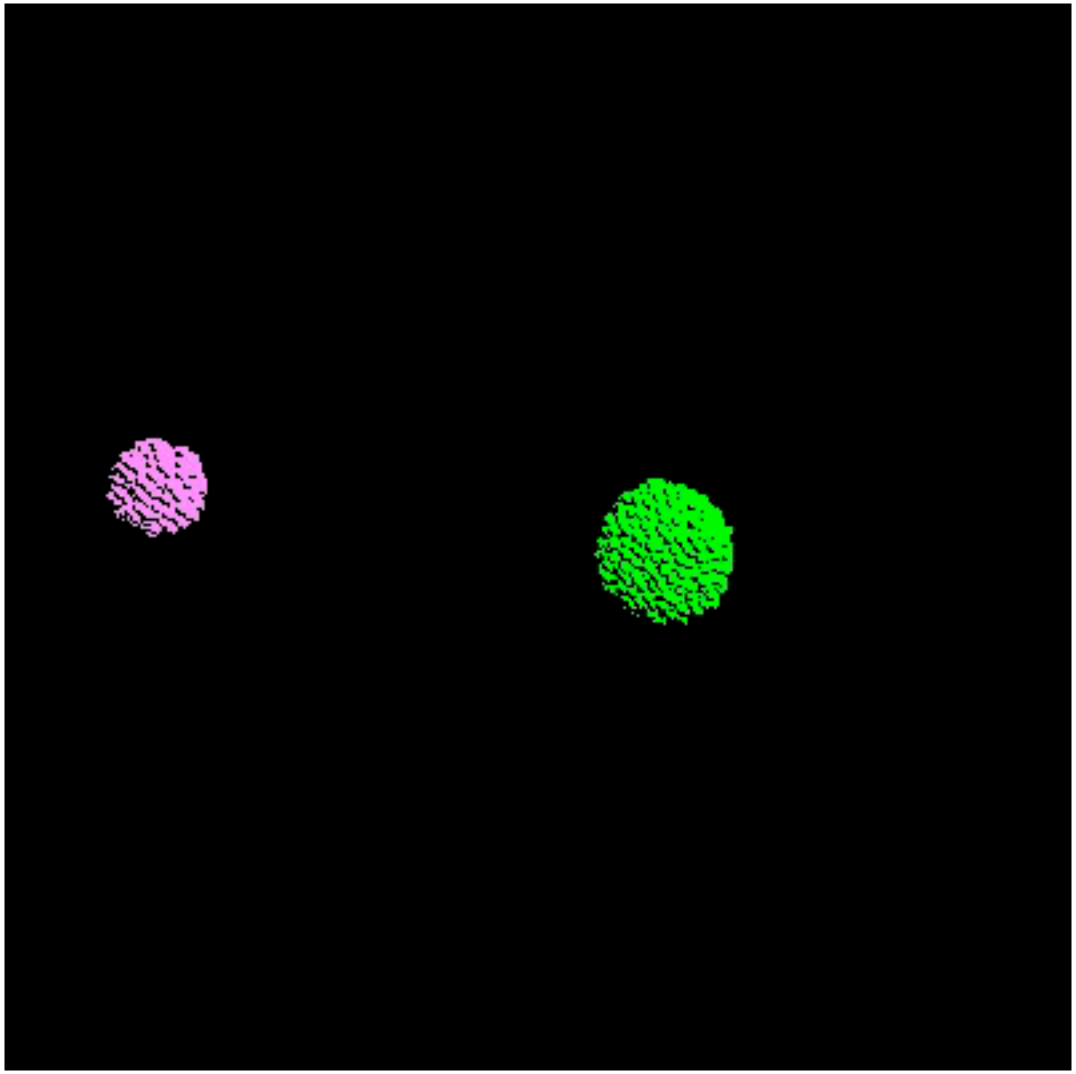

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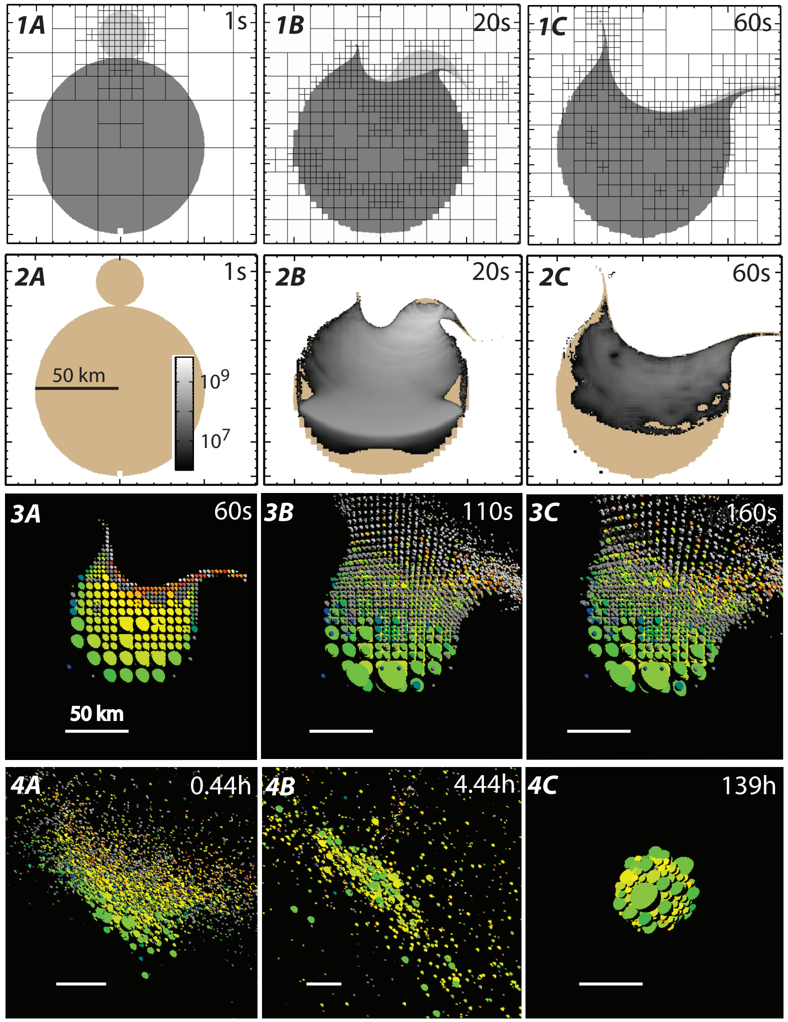
Numerical Method for Supersonic Collisions

- Hybrid shock hydro (**`CTH`**) to N-body gravity (**`pkdgrav`**) to model gravitational re-accumulation

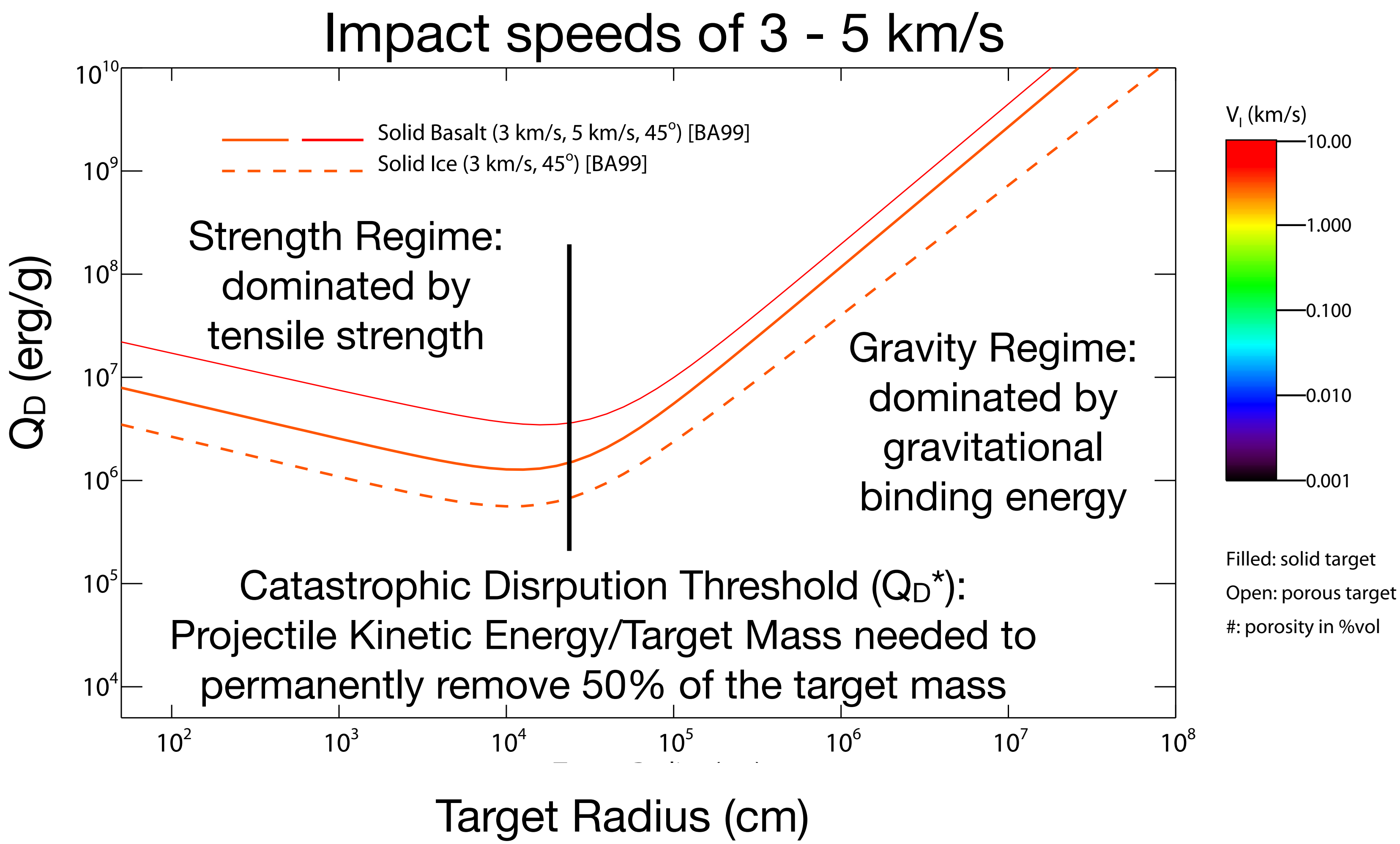
- Impacts into non-porous basalt targets with material strength (weak - strong)

- Impact speed kms/s, target radius = 1 - 50 km, mass of target much larger than mass of projectile

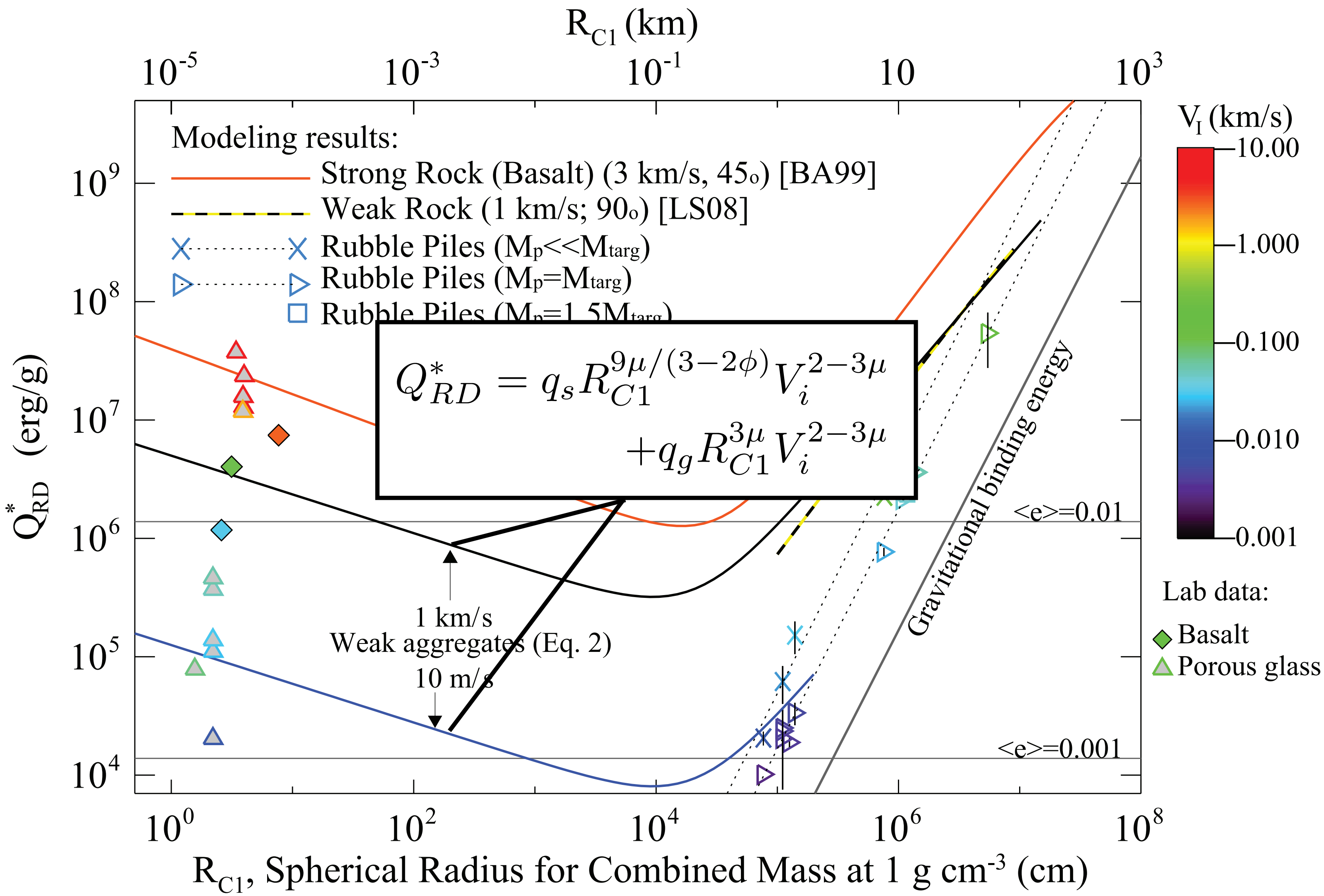


Leinhardt & Stewart, 2009

First Order Collision Outcomes: Example Q_D*



Collision Outcome: Velocity dependent Q_{RD}*

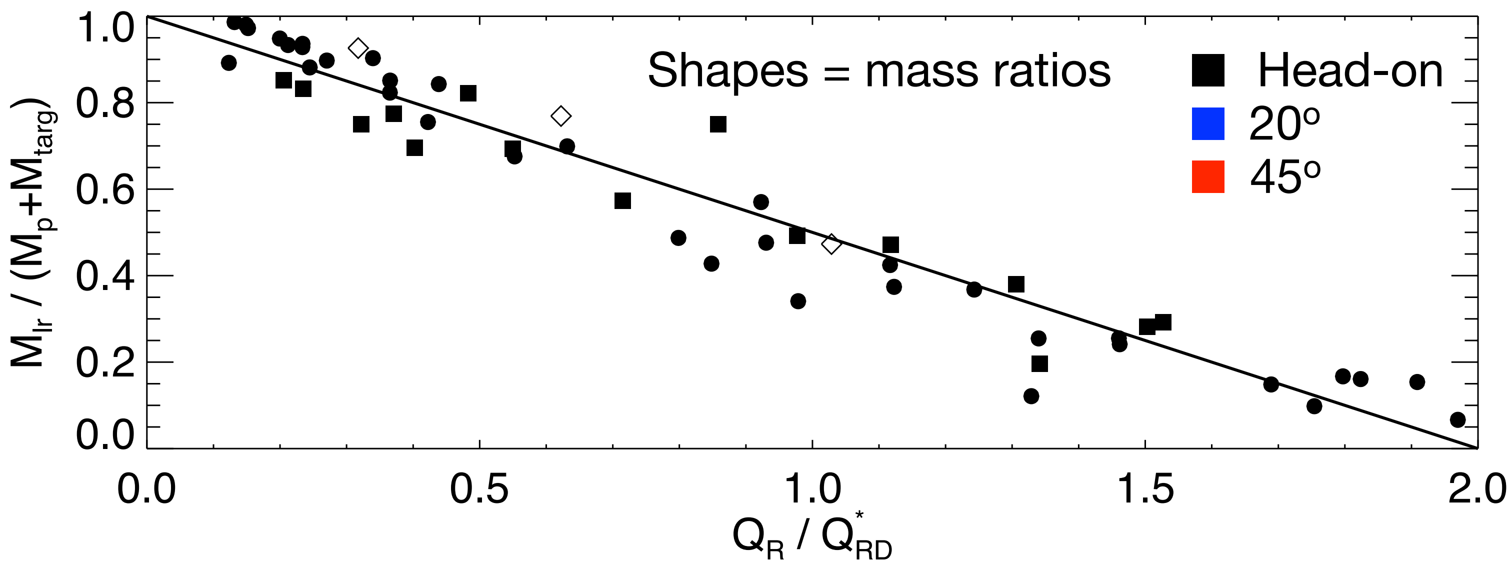


$$Q^*_{RD} = q_s R_{C1}^{9\mu/(3-2\phi)} V_i^{2-3\mu} + q_g R_{C1}^{3\mu} V_i^{2-3\mu}$$

Stewart & Leinhardt, 2009

Collision Outcome: Universal Law for M_{lr}

- Mass of the largest remnant is correlated with energy of impact (universal law)
- Universal law is effectively independent of mass ratio and impact angle when normalising by M_{tot} and Q^{*}_{RD}



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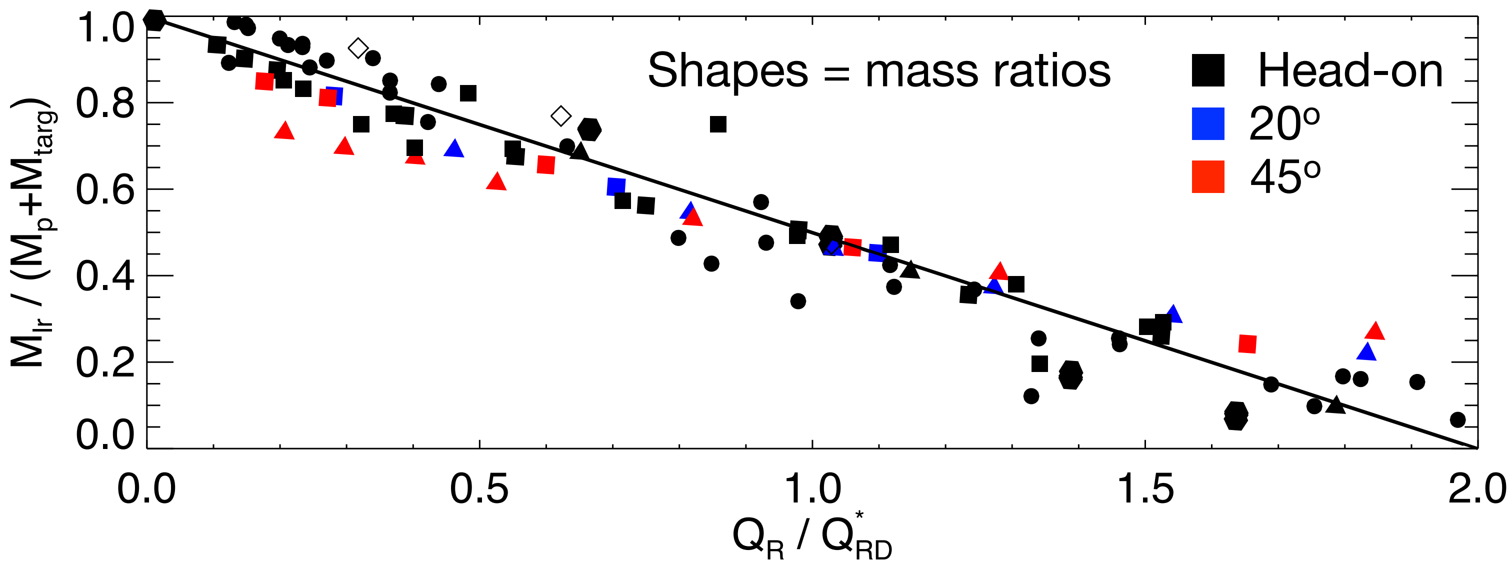

Wednesday, June 30, 2010

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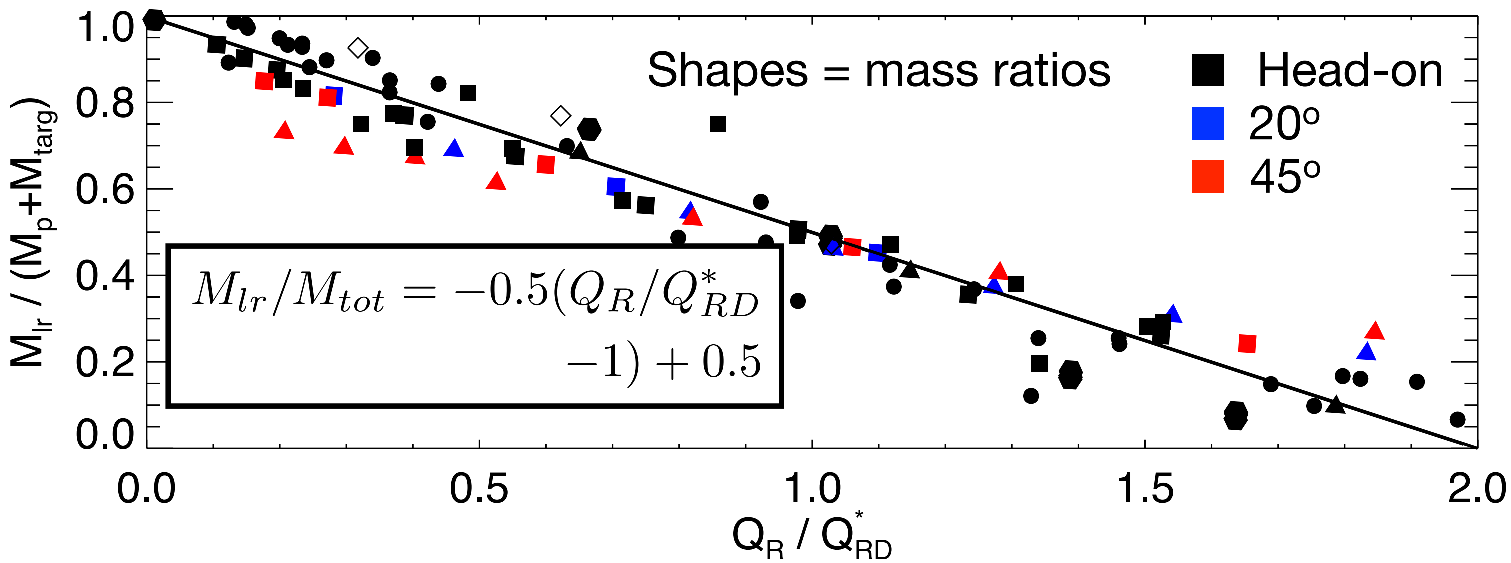
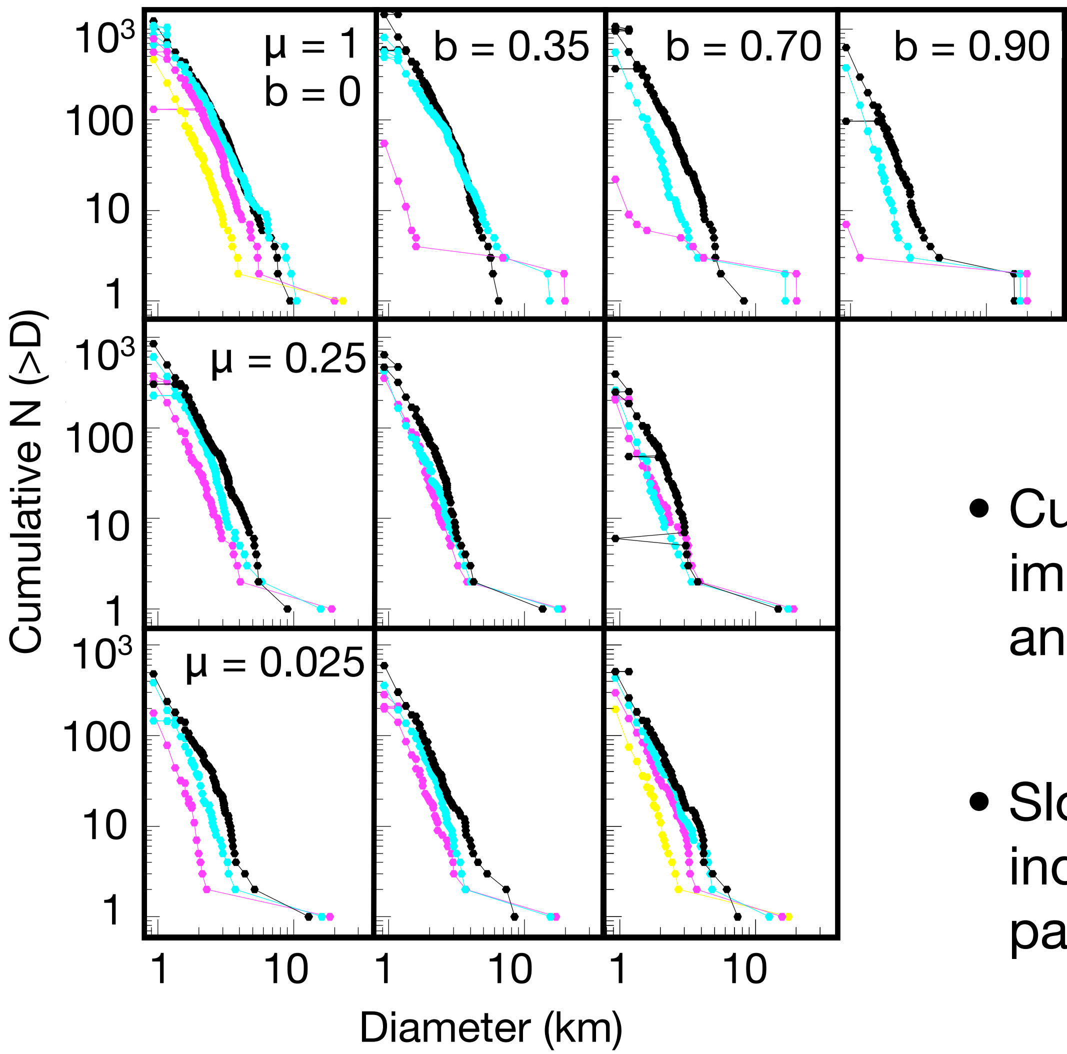


Size Distribution



- Cumulative size distribution for various impact speeds, impact parameters, and mass ratios

- Slope of fragment tail (~ -3.5) is independent of mass ratio and impact parameter

Summary of Collision Outcome Model (to date)

- Q^*_{RD} varies by orders of magnitude during formation of solar system (Benz & Asphaug ‘99; Benz ‘00; Leinhardt & Stewart 2009; Stewart & Leinhardt 2009)

- Small gravity dominated bodies are weaker than previously assumed because of efficient energy coupling during low-speed collision events

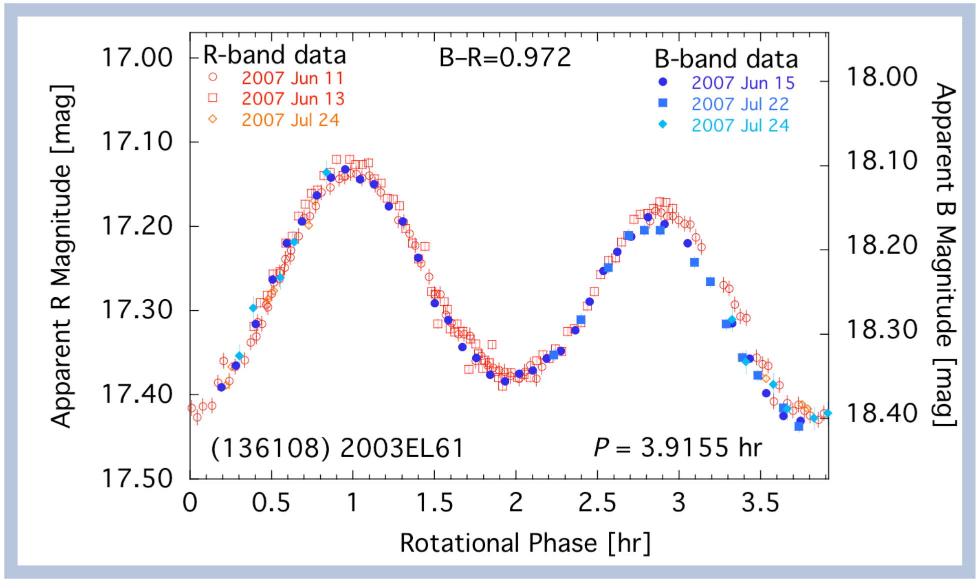
- New variables define universal law for M_{lr}/M_{tot} vs Q_R/Q^*_{RD} that is relatively independent of impact parameter and mass ratio

- Size distribution of collisional tail independent of mass ratio and impact parameter (cumulative power-law index -3.5 differential -4.5)

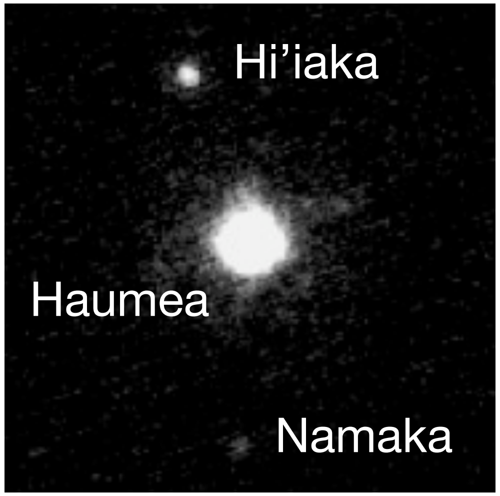
- Leinhardt & Stewart (in prep) equations to fully characterise collision outcome as a function of mass ratio and impact parameter where relevant: universal law, catastrophic disruption curve, <v>, size distribution, transition to graze and run regime

Haumea & Minions

- Large & elongated @ 43 AU:
  Radii ~1000 x 750 x 500 km
- Homogeneous surface & neutral colour
- Fast spin period ~ 4 hr
- 2 satellites + 8 family members
  (first “family” in the KB but many in the asteroid belt)
- Mass of Haumea satellites + family ~ 0.01 M_H
- Family velocity dispersion low ~ 150 m/s
  (Refs: Rabinowitz 2006, Ragozzine & Brown 2007 & 2009, Schaller & Brown 2007 & 2008)



Lacerda et al. 2008

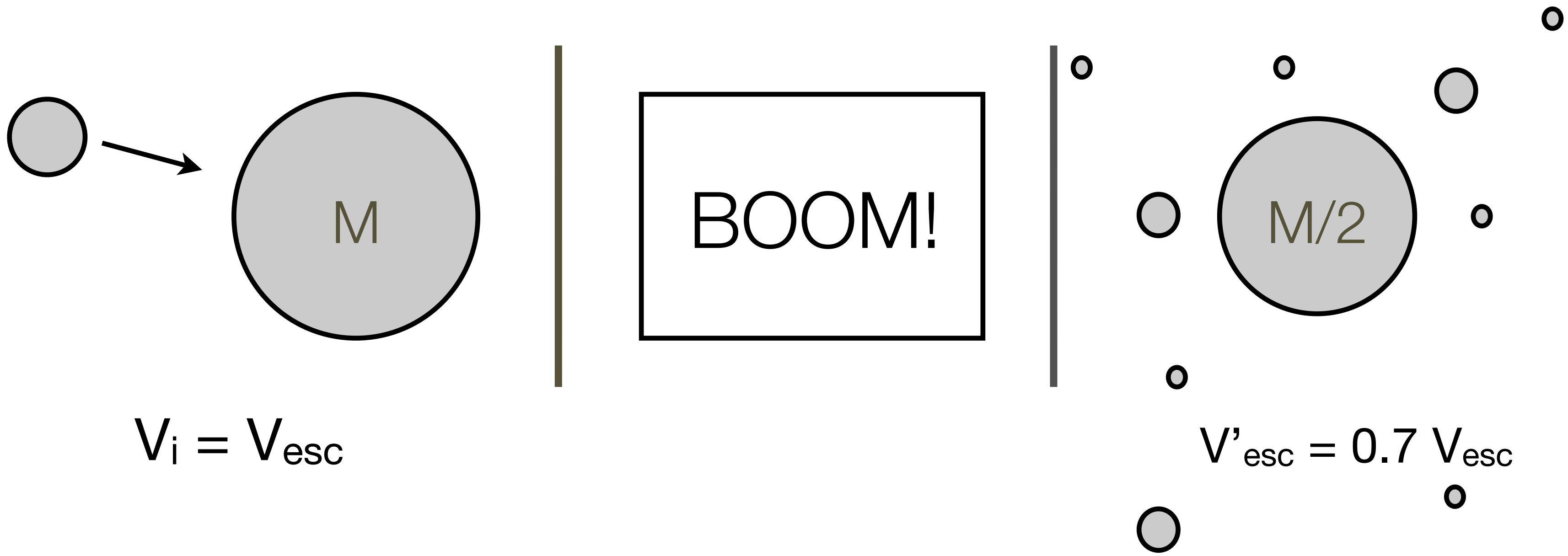


Brown et al. 2006

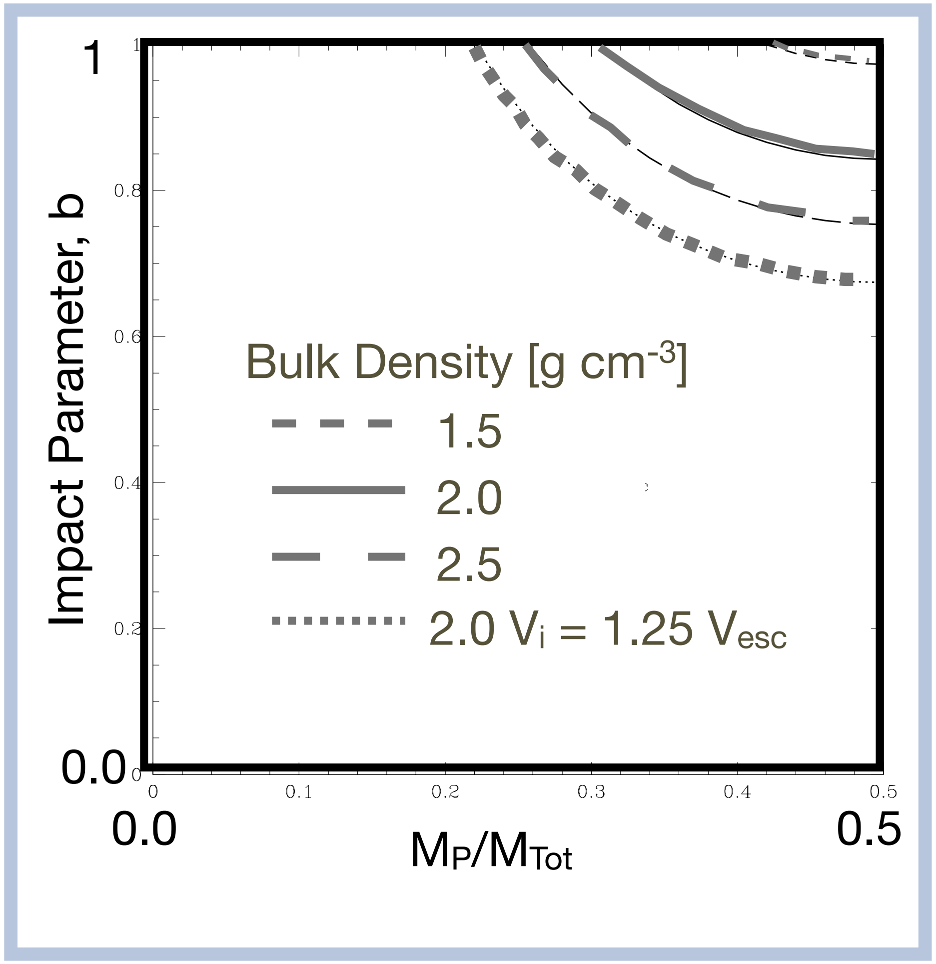
Slow Collision?

- Velocity dispersion of family members is small in comparison to escape speed from Haumea, $V_{disp} < V_{esc}$ from Haumea (900 m/s)

- Asteroid families have velocity dispersions ~ escape speed from largest remnant $M_{lr} \sim 0.5\ M_{Targ}$



What about the Spin?



Leinhardt et al. 2010

- Assume all L of projectile and target goes into Haumea
- Analytic prediction of impact parameters

$$b = \frac{L}{L_{\rm crit}} \frac{k}{\sqrt{2} f(\gamma)} \frac{V}{V_{\rm esc}}$$

(Canup 2005)

- Parameter space to attain required spin is narrow

Numerical Method

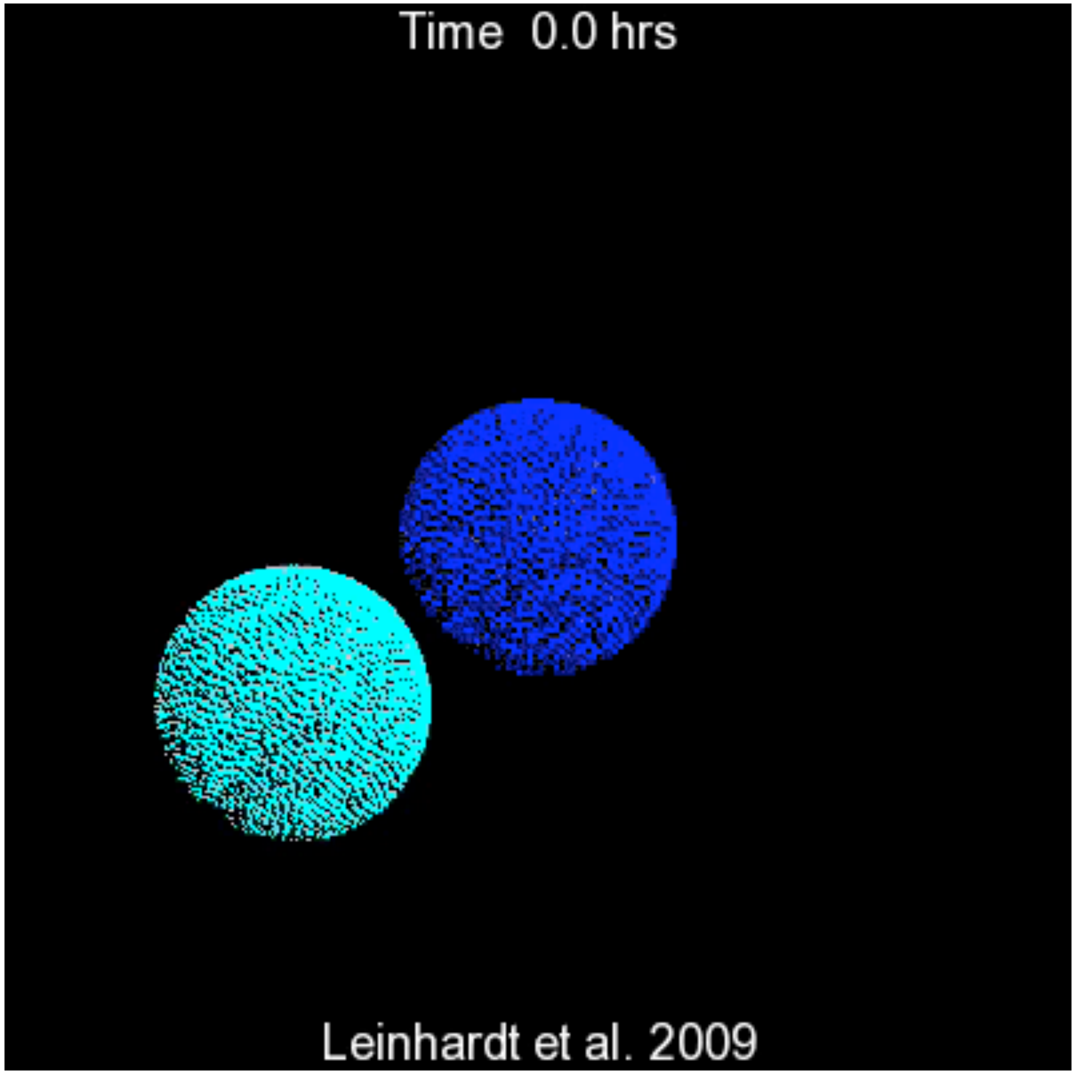
- Numerically difficult problem - family members much smaller than Haumea (requiring high resolution), collision is slow (requiring long integration time), large amount of energy in impact (need equations of state)

- Refine parameter space: Low resolution numerical simulations (using a gravity code only) over a range of parameter space to locate best match to Haumea

- A few high resolution hybrid simulations (using two numerical methods) of the most promising scenarios to find the best match to entire family

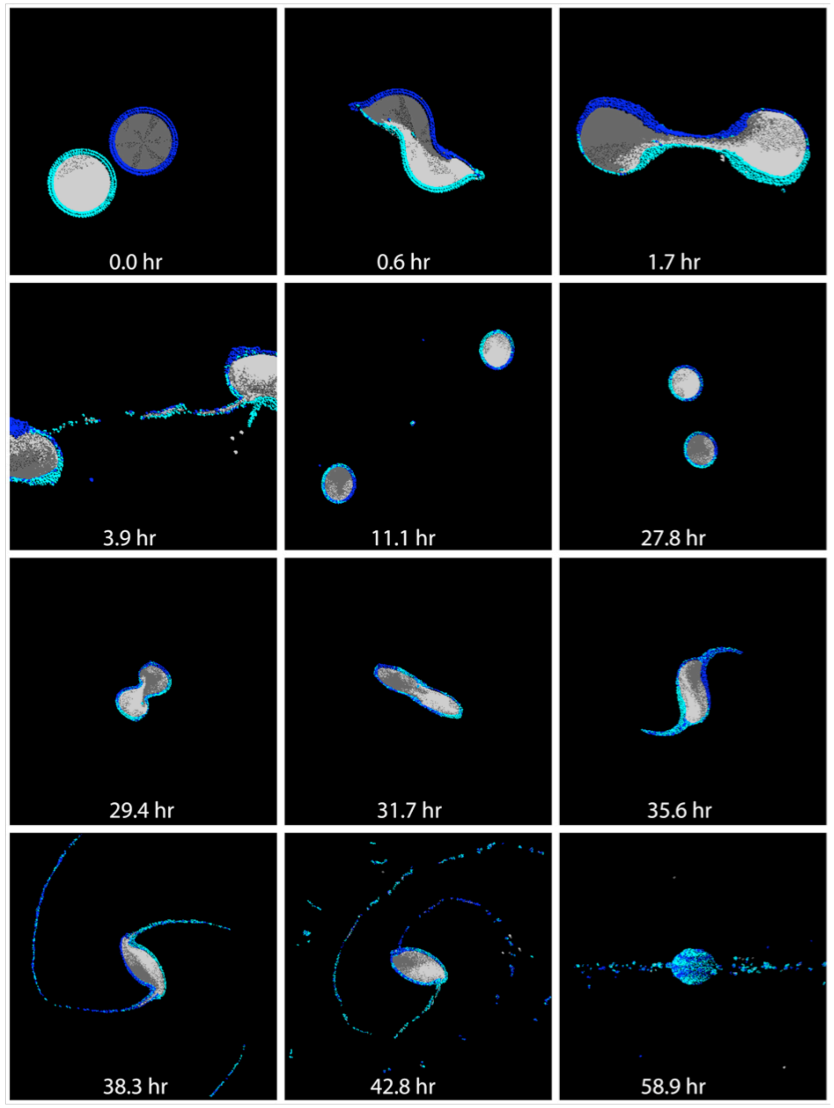
Graze and Merge

- $M_{proj} = M_{targ}$
- R = 650 km
- V_i = 900 m/s
- b = 0.6
- Ice mantle over rock core (bulk density 2 g/cm^3)
- Gadget + pkdgrav (hydrocode with EOS for ice & rock + N-body gravity code)



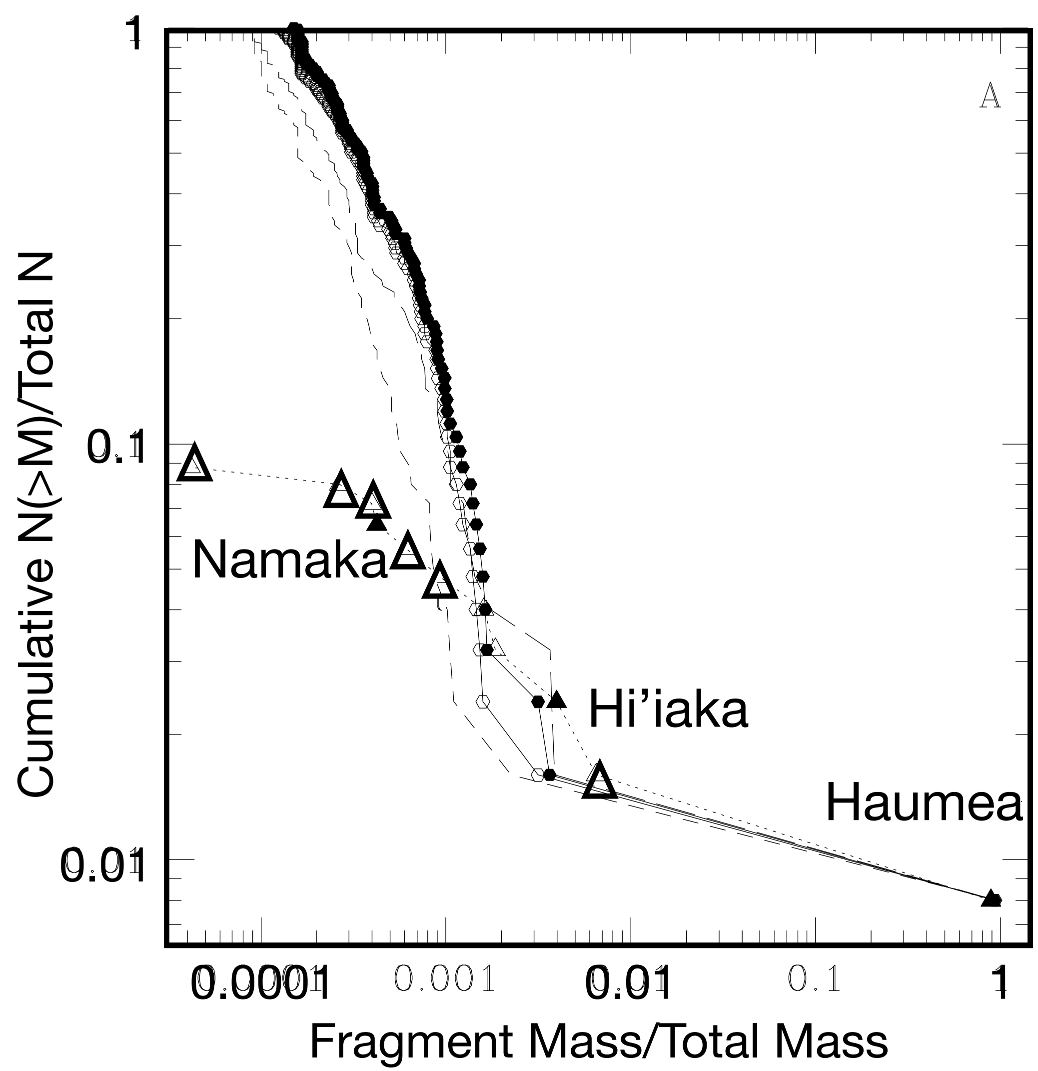
Graze and Merge Cont.

- Icy mantles blue, rocky cores grey
- Little mass loss on first impact
- Cores merge quickly on second impact
- Mass loss of mantle due to fission - largest remnant is initially spinning above critical spin rate
- Satellites and family members released close to escape speed



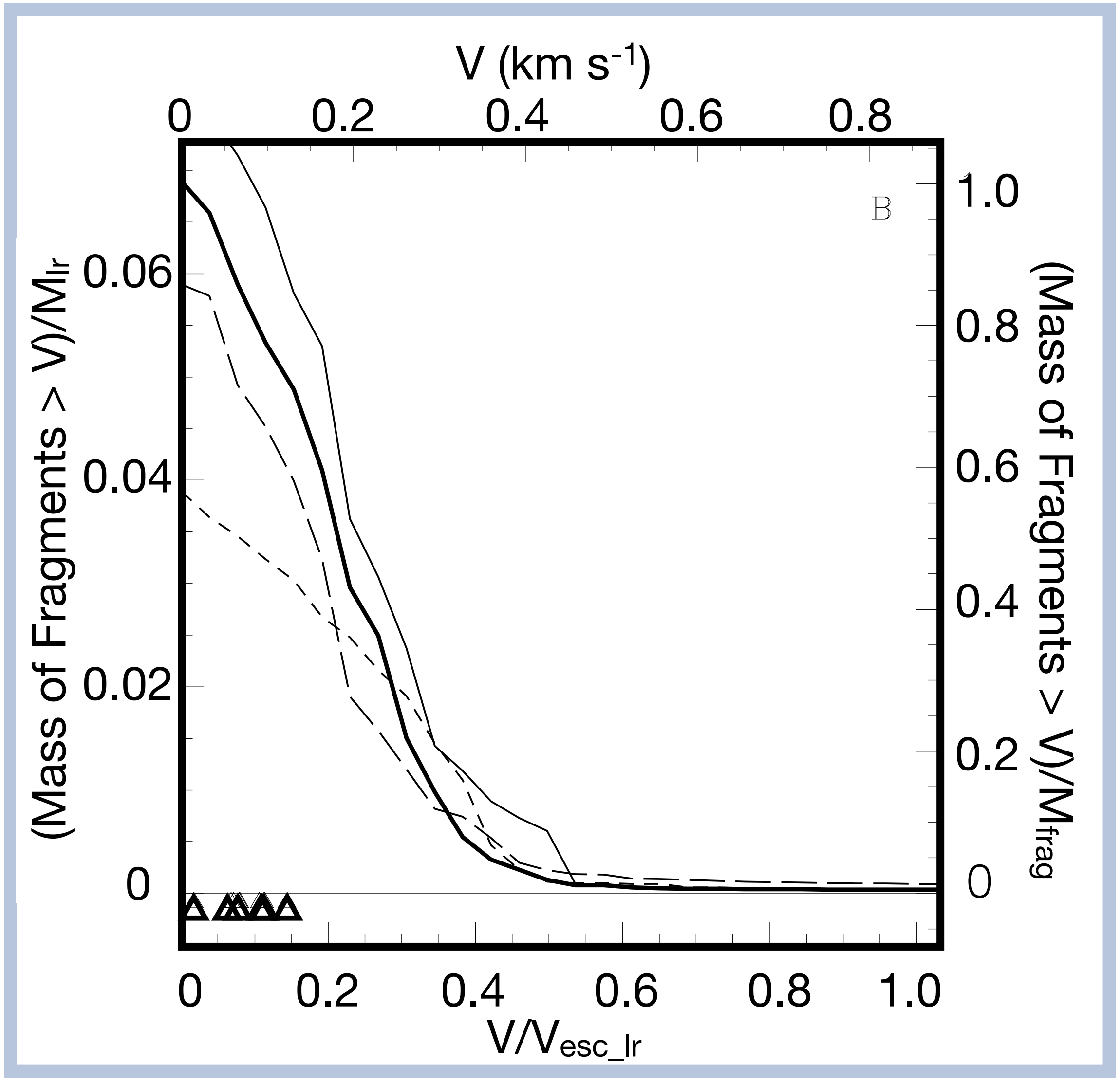
Results of Graze and Merge: Size Distribution

- Mass of observed family members derived assuming albedo of 0.7 and bulk density of 1.0
- Match mass, spin, and elongation of Haumea and mass largest family members
- Observed family is incomplete



Leinhardt et al. 2010

Results of Graze and Merge: Velocity Dispersion



- 35 stable satellites after 2000 spin orbits of largest remnant
- Family mass small (.07 M_{lr})
- Satellites and family made of mantle material (.8 M_F)
- Satellites have low velocity dispersion (V_{inf} < 0.5 V_{esc})

Leinhardt et al. 2010

When and Where?

- If the collision scenario presented here is correct Haumea + family are old but not that old - the family could only have formed at the end Kuiper Belt excitation/sculpting event

- Dynamically hard to have the impact that is numerically the best fit --- still trying to figure out how to do it. Need two massive bodies for graze and merge collision modelled in this paper - not possible in recent past. Not clear that it is ever possible.

- Haumea is currently in classical belt but that could be the result of the impact: the impact could have occurred in scattered disk and the result ended up in classical belt (Levison et al. 2008) this collision is very slow though ...

What does this all mean for planet formation?

- km-size range is weak: 1) km size needs to be avoided; 2) protected; or 3) the 1 km planetesimals do get ground down but a few are spared and grow fast by accreting the debris of those that were not so lucky (Paardekooper & Leinhardt 2010)

- Phases must overlap and interact our theoretical model is still too simple - in order to connect directly with observations our models of planetesimal evolution must become more realistic

- The Haumea collisional family is an extreme example of a collisional family in the Kuiper Belt there must be more in the Kuiper Belt when found would constrain the collisional and dynamical evolution of the outer solar system