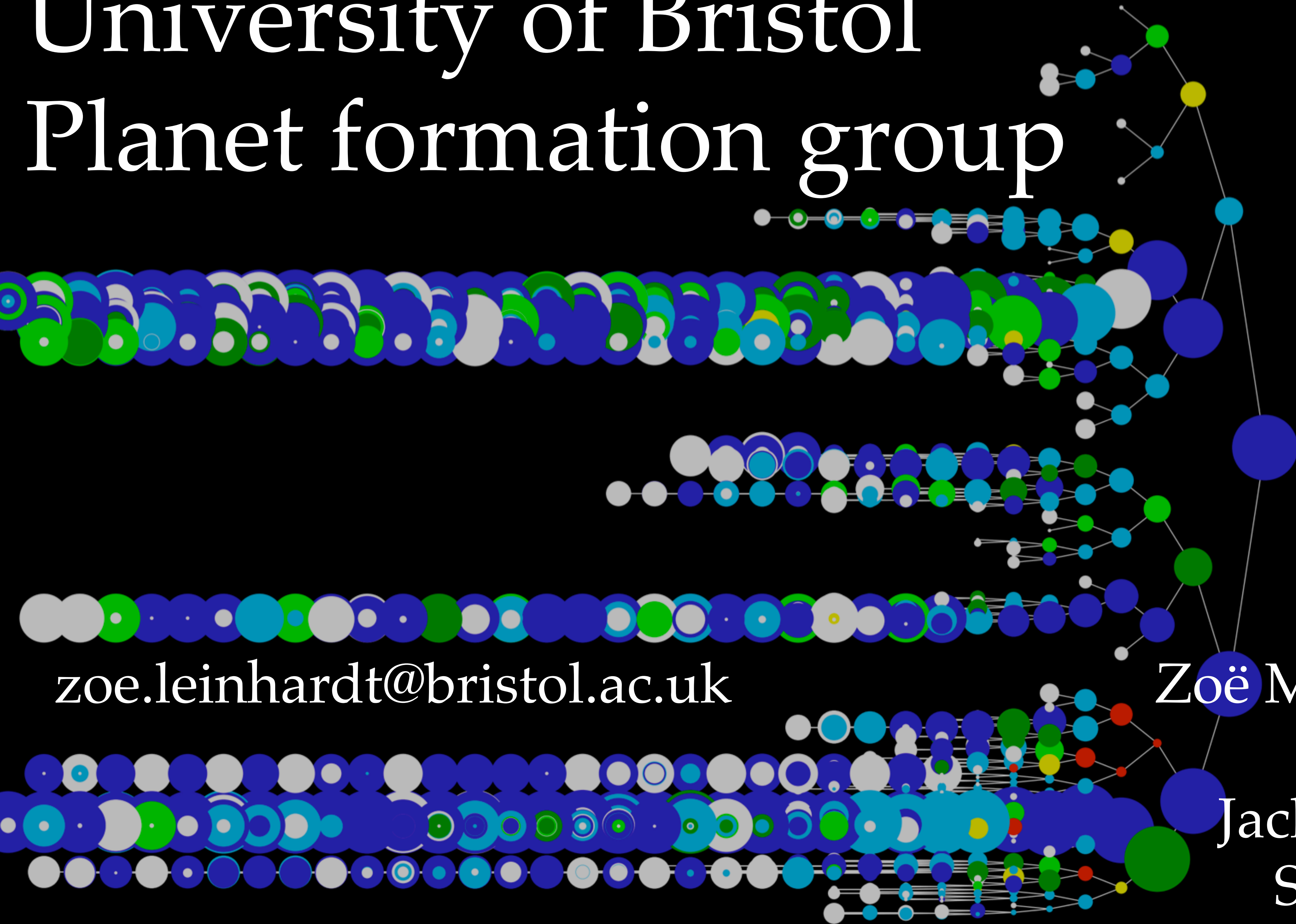
University of Bristol Planet formation group



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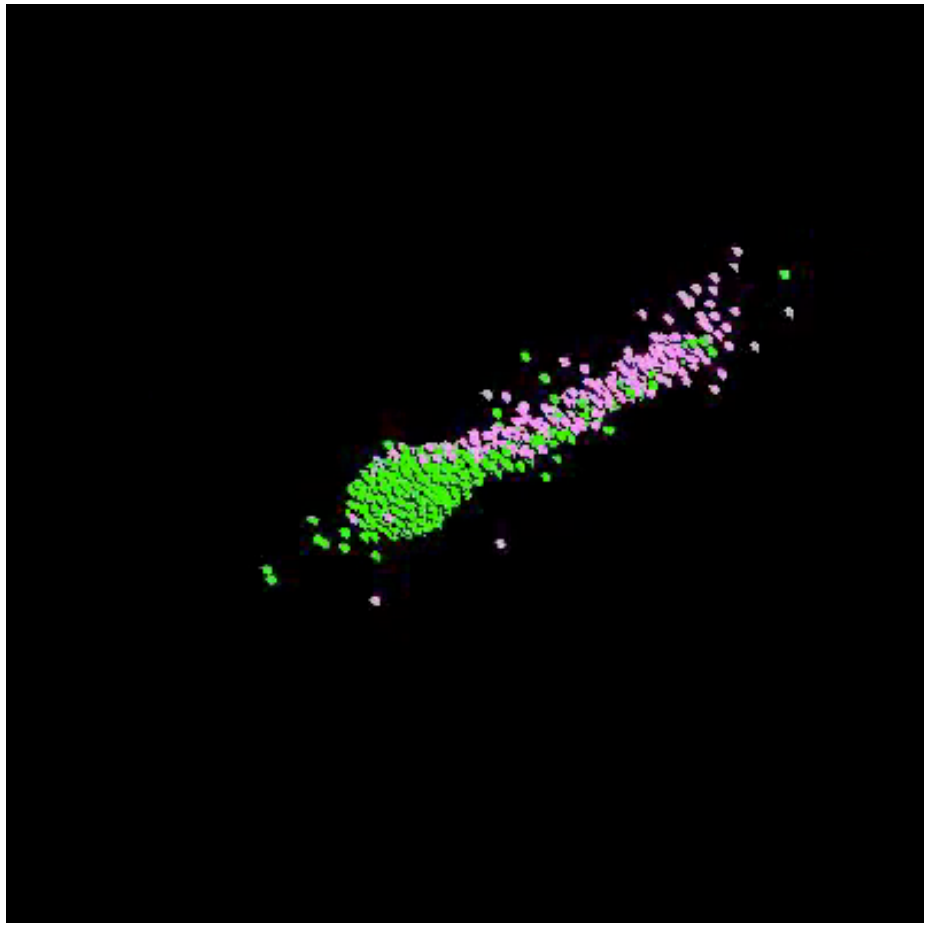
http://www.star.bris.ac.uk/planets

Role of collisions in the formation & evolution of planets

- Regardless of how the solar system formed collisions played an important role - i.e. giant impacts & asteroid family forming events
- Evidence for early planetesimal differentiation: ~Myr timescale (Kleine et al. 2005; Schersten et al. 2006; Markowski et al. 2006)
- Erosion of a differentiated body could result in compositional change (Asphaug et al. 2006; Marcus et al. 2010; Stewart & Leinhardt, 2012). What happens as a result of multiple accretion-dominated collisions?

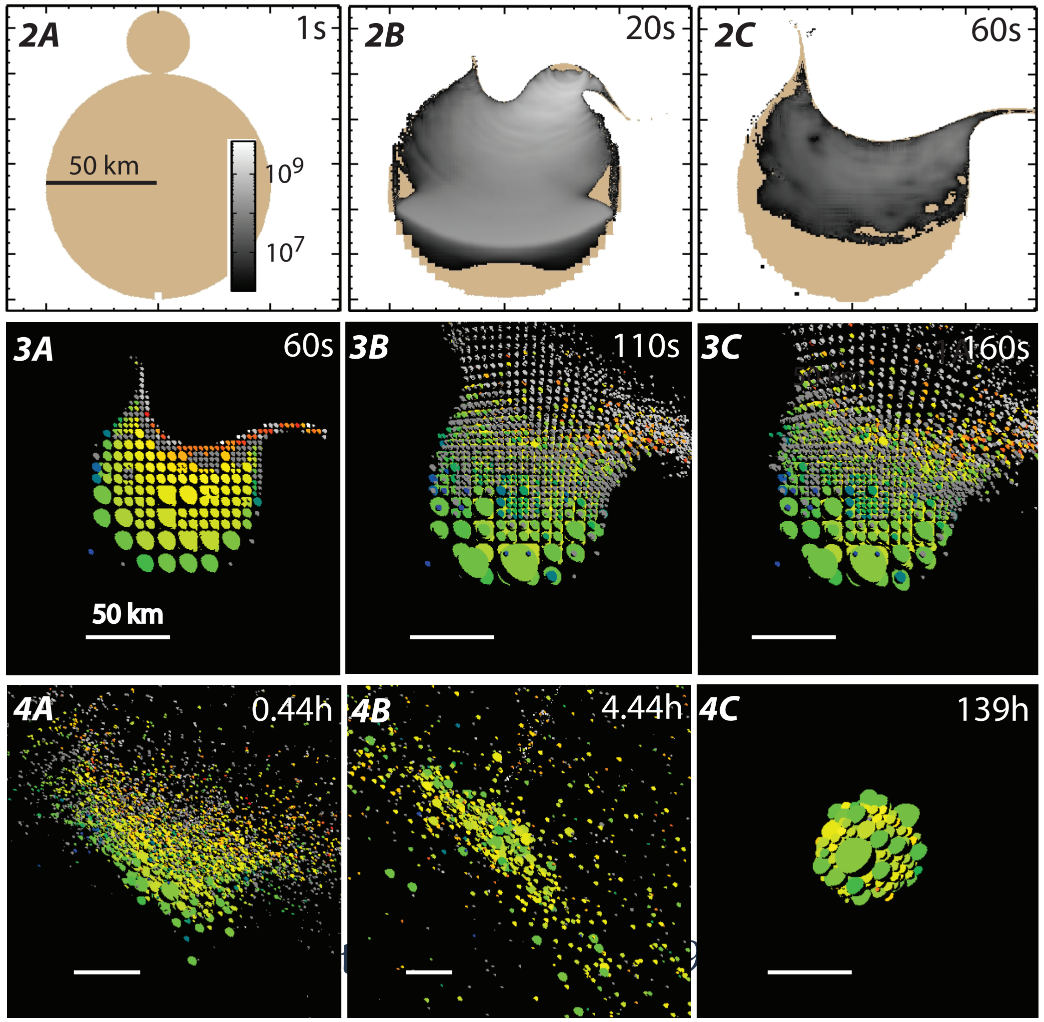
Numerical Method: Building a Collision Model

Slow Collision (sub-sonic)
N-body integrator, rubble-pile impactors

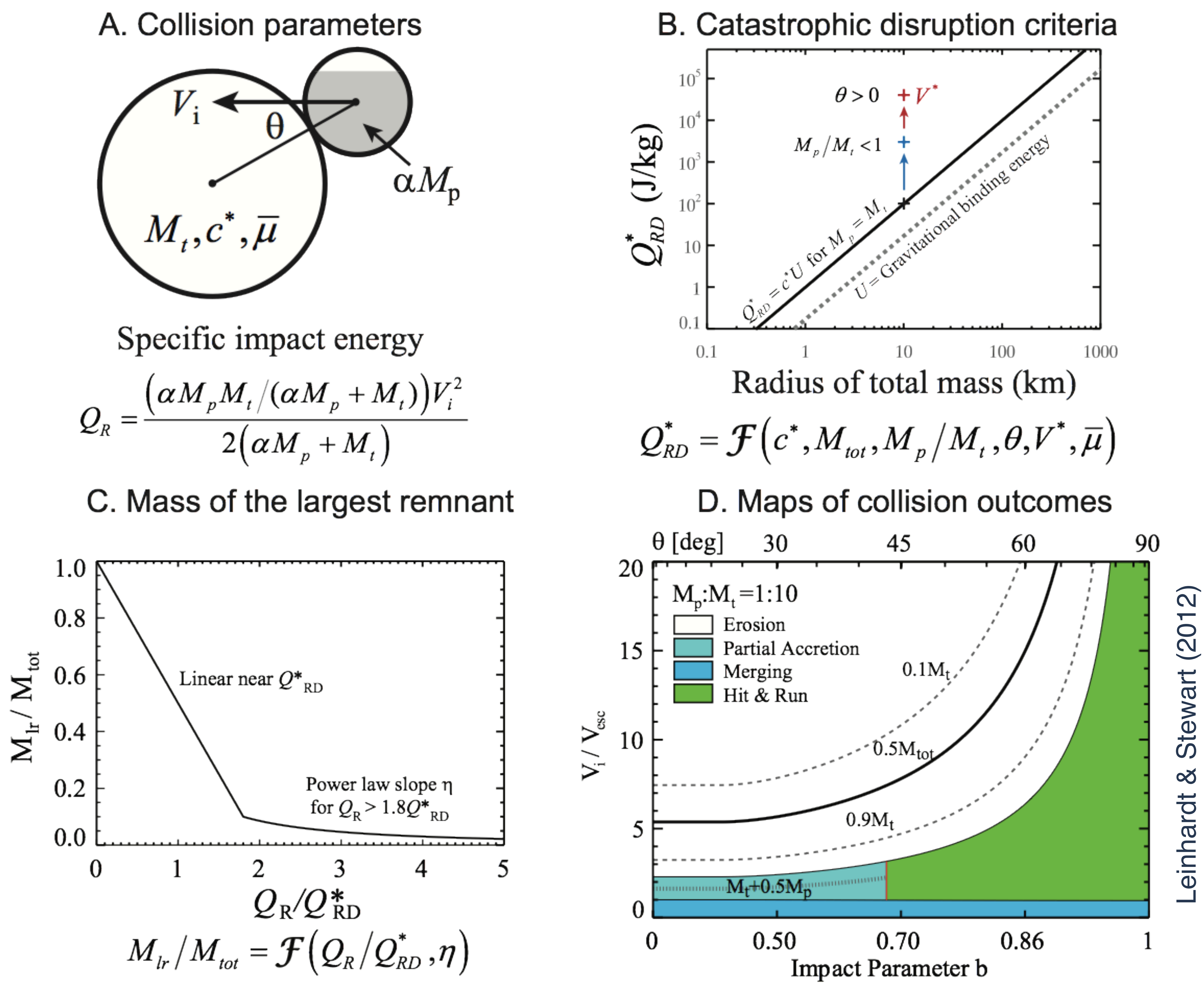


Leinhardt & Richardson (2002)

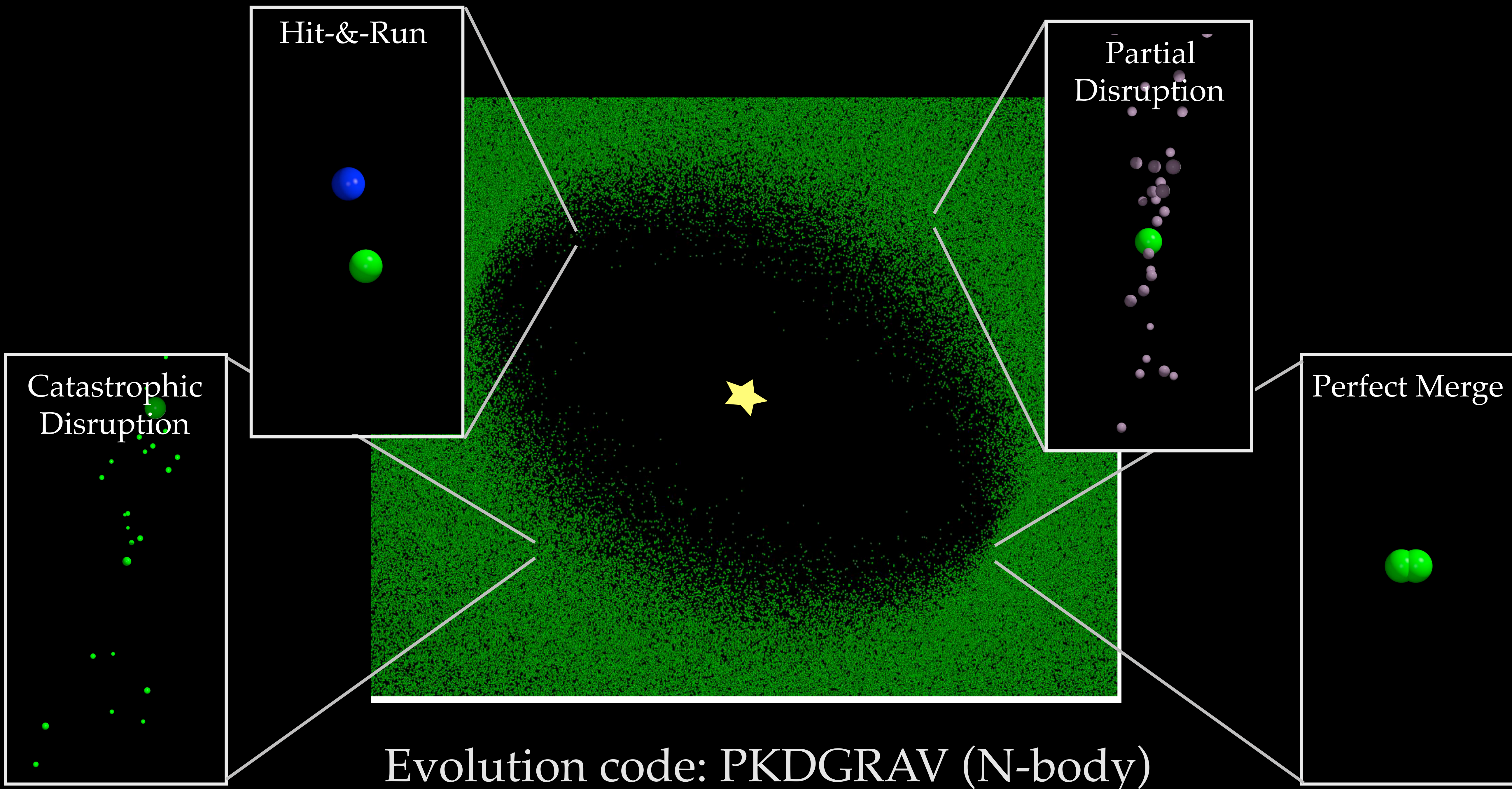
Fast Collision (super-sonic)
Hybrid: hydro + N-body



Simulate broad range of collisions in isolation. Fit scaling-laws to outcomes.
Incorporate empirically derived collision model into planet formation code.

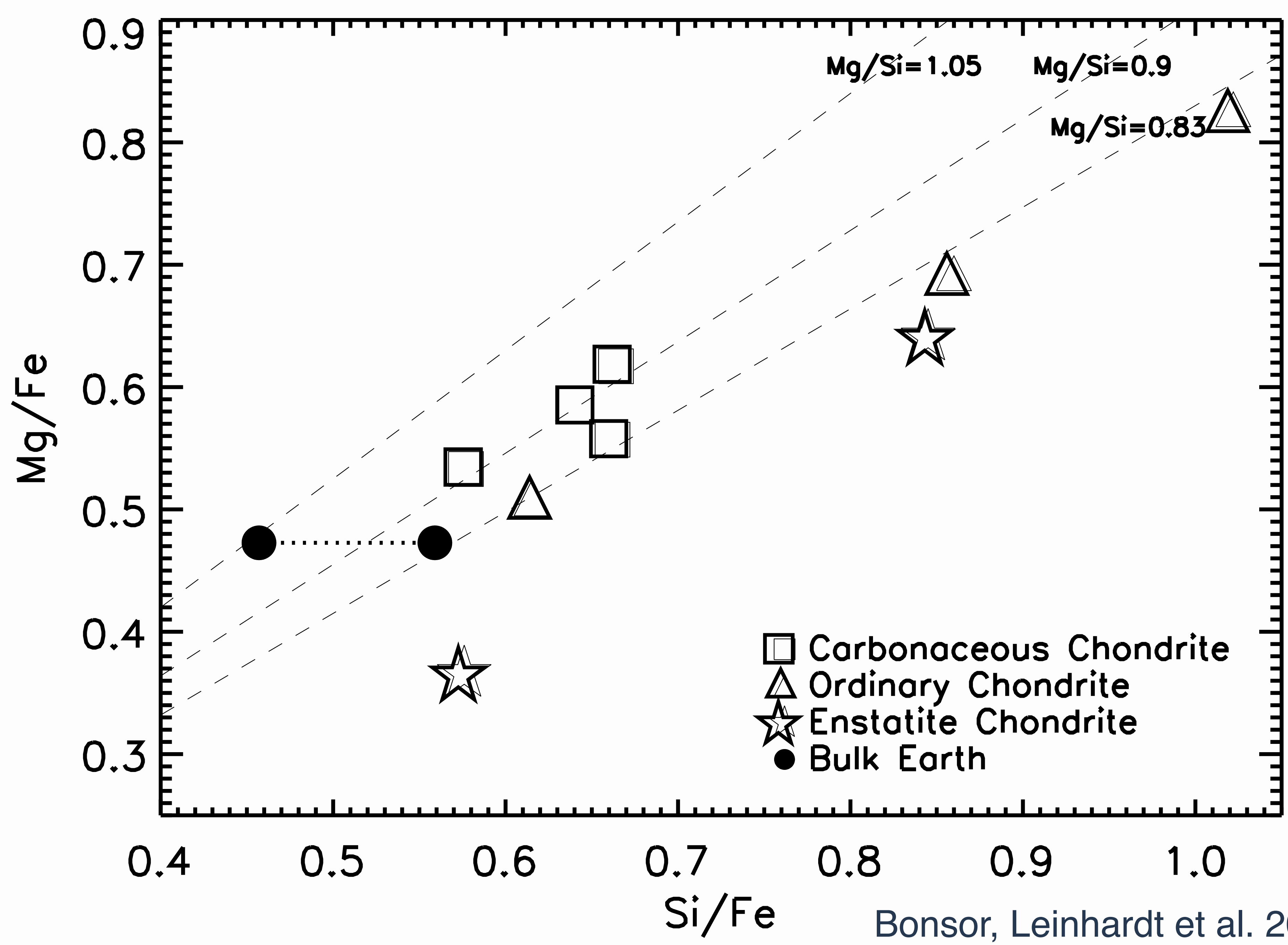

A. Collision parameters
V_i
θ
αM_p
$M_t, c^*, \bar{\mu}$
Specific impact energy
$Q_R = \frac{(\alpha M_p M_t / (\alpha M_p + M_t)) V_i^2}{2(\alpha M_p + M_t)}$
B. Catastrophic disruption criteria
$\theta > 0$
V^*
$M_p / M_t < 1$
$Q^*_{RD} = c^* U$ for $M_p = M_t$
U = Gravitational binding energy
Q^*_{RD} (J/kg)
Radius of total mass (km)
$Q^*_{RD} = \mathcal{F}(c^*, M_{tot}, M_p / M_t, \theta, V^*, \bar{\mu})$
C. Mass of the largest remnant
Linear near Q^*_{RD}
Power law slope η for $Q_R > 1.8 Q^*_{RD}$
M_{lr} / M_{tot}
Q_R / Q^*_{RD}
$M_{lr} / M_{tot} = \mathcal{F}(Q_R / Q^*_{RD}, \eta)$
D. Maps of collision outcomes
θ [deg]
$M_p : M_t = 1:10$
Erosion
Partial Accretion
Merging
Hit & Run
$0.1M_t$
$0.5M_{tot}$
$0.9M_t$
$M_t + 0.5M_p$
V_i / V_{esc}
Impact Parameter b
Leinhardt & Stewart (2012)

Collision Model & N-body Code



Evolution code: PKDGRAV (N-body)
Collision model: EDACM
$N_{init} = 10^5$, resolution limit ~ 100 km, f = 6

The Non-chondritic Earth

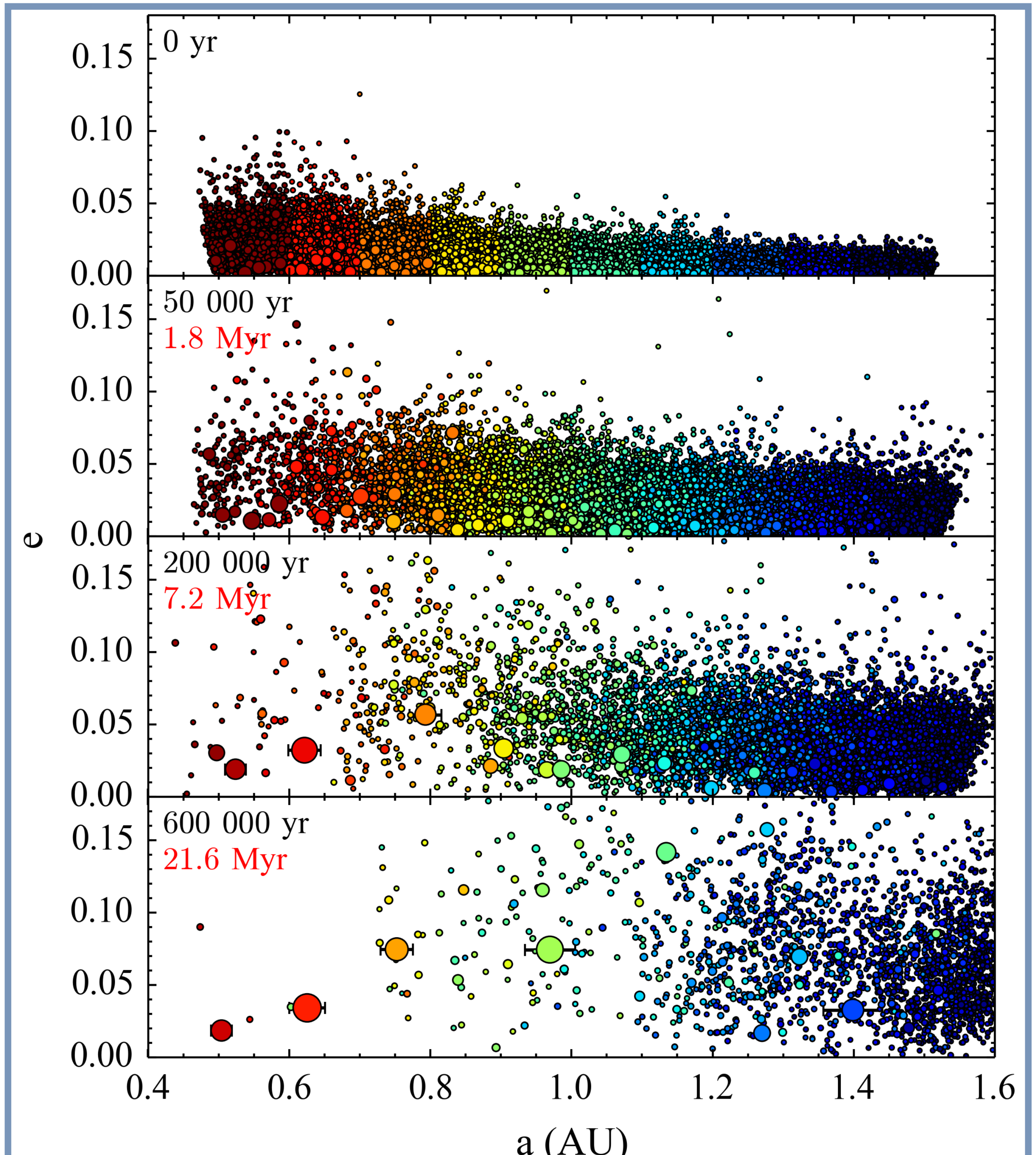


Bonsor, Leinhardt et al. 2015

1. Hidden reservoir
2. Heterogeneous nebula

- Collisions

Formation of Terrestrial Embryos with EDACM



Colour:

A. Proxy for composition, indicates degree of radial mixing

B. Calculated using a mass-weighted histogram of all material accreted by each particle

Time:

A. Particles are radially inflated (f = 6) to accelerate evolution

B. Effective time ~ f^2 x simulated time

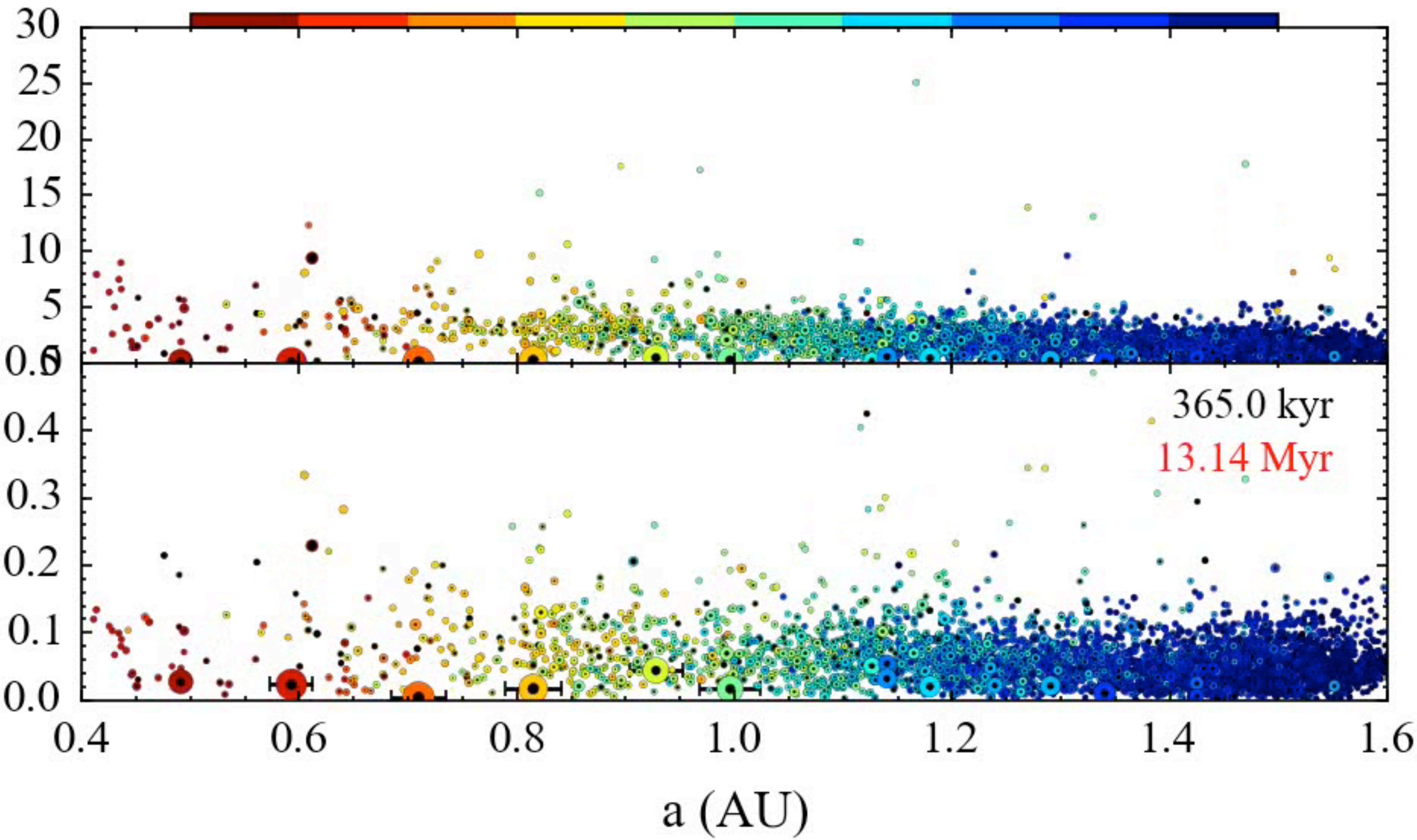
Other:

A. Particle size proportional to radius

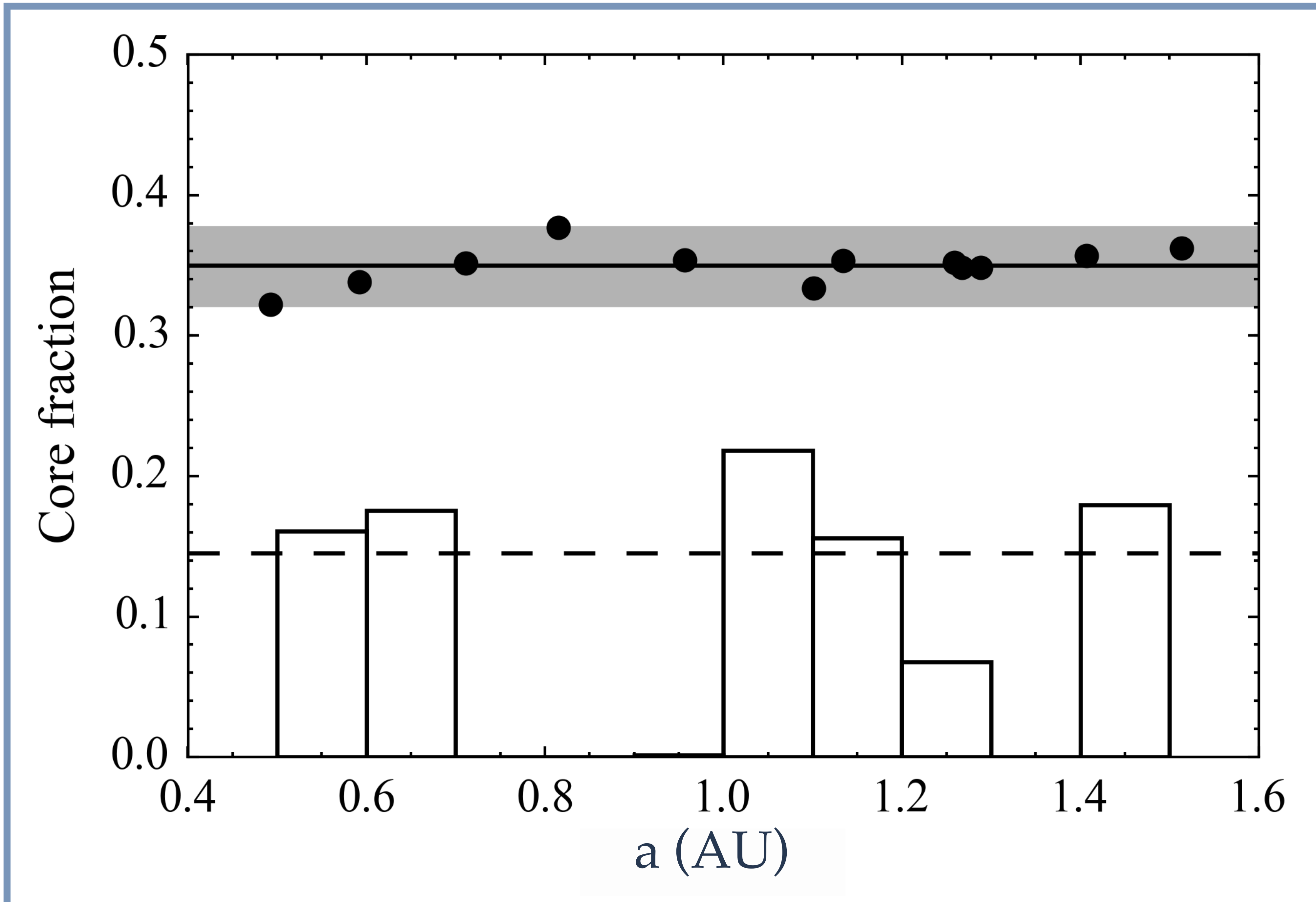
B. Protoplanets - gravitational extent indicated by error bars

Bonsor, Leinhardt et al. 2015

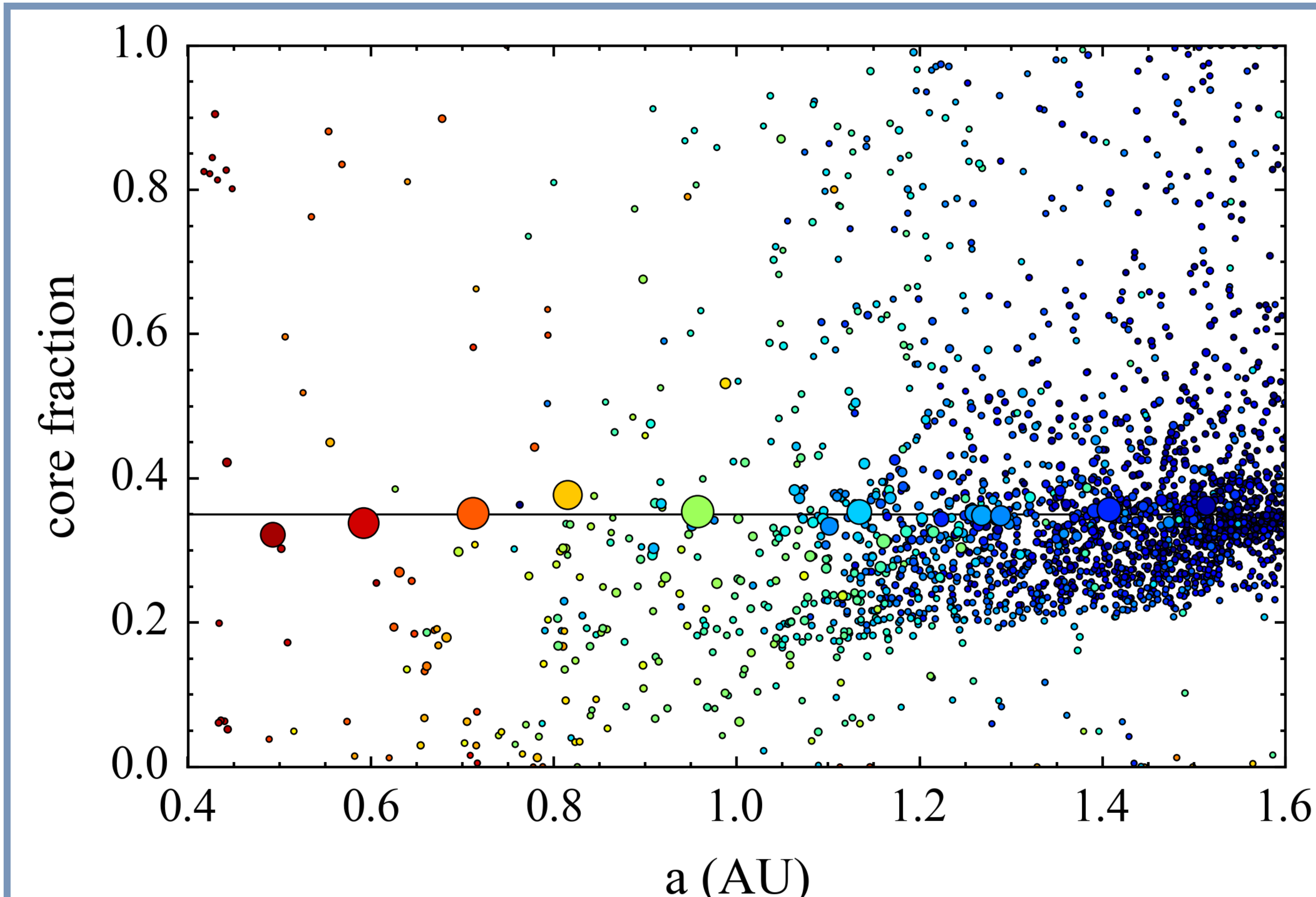
Embryo Formation with Core/Mantle Tracking



Core Fraction of Largest and Smallest Mass

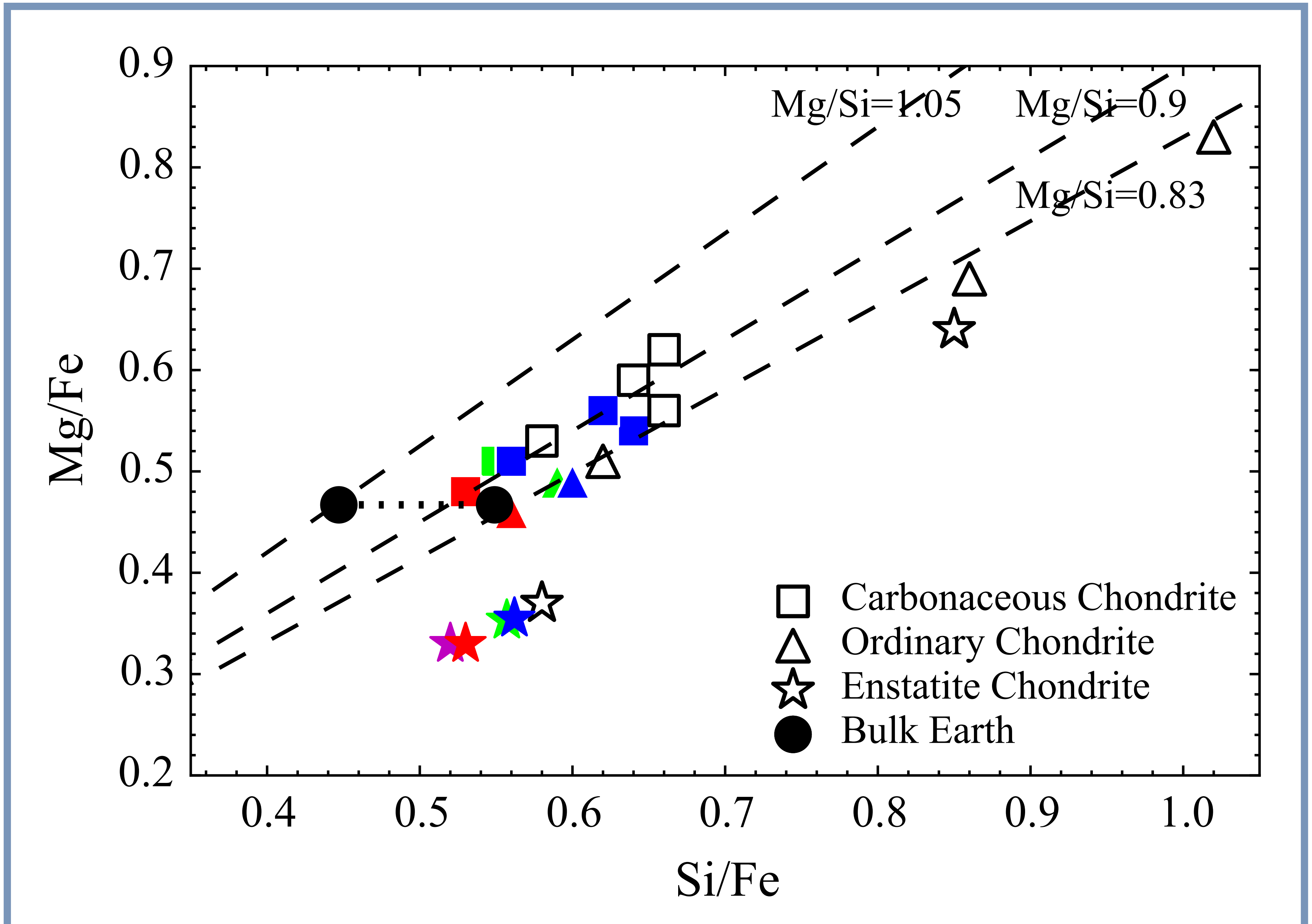


Core Fraction of Resolved Particles



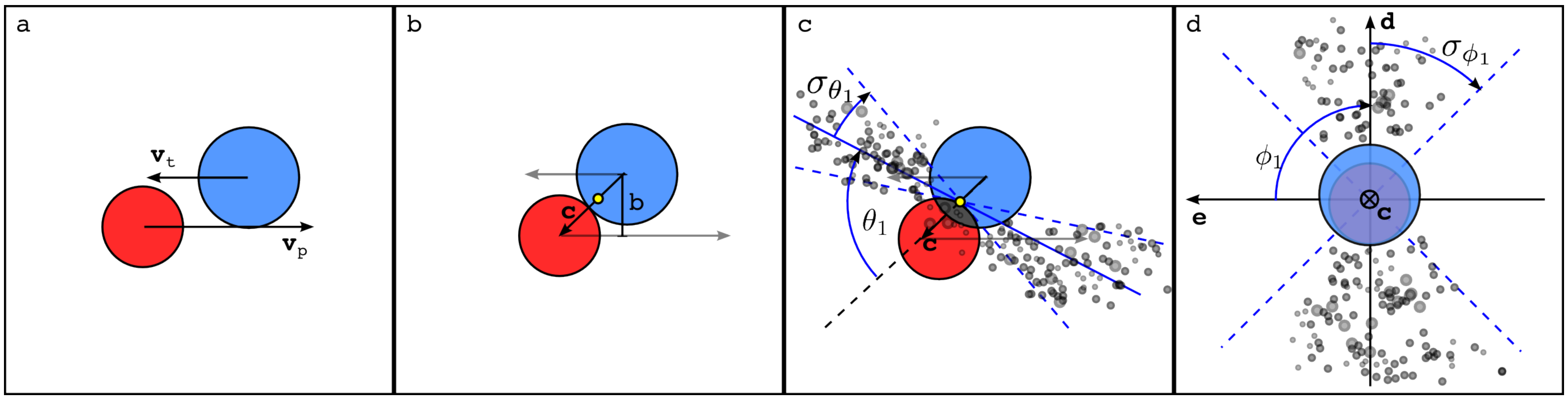
Carter et al., in prep

The Non-chondritic Earth



Carter et al., in prep

Model Fragment Distribution of Collisions



- Fragments produced in a collision are ejected in a range of patterns
- Two main patterns: Jets and Disks
- Variation of theta and phi gives a range of patterns from jet-like to disk-like

Leinhardt, Dobinson et al., in press

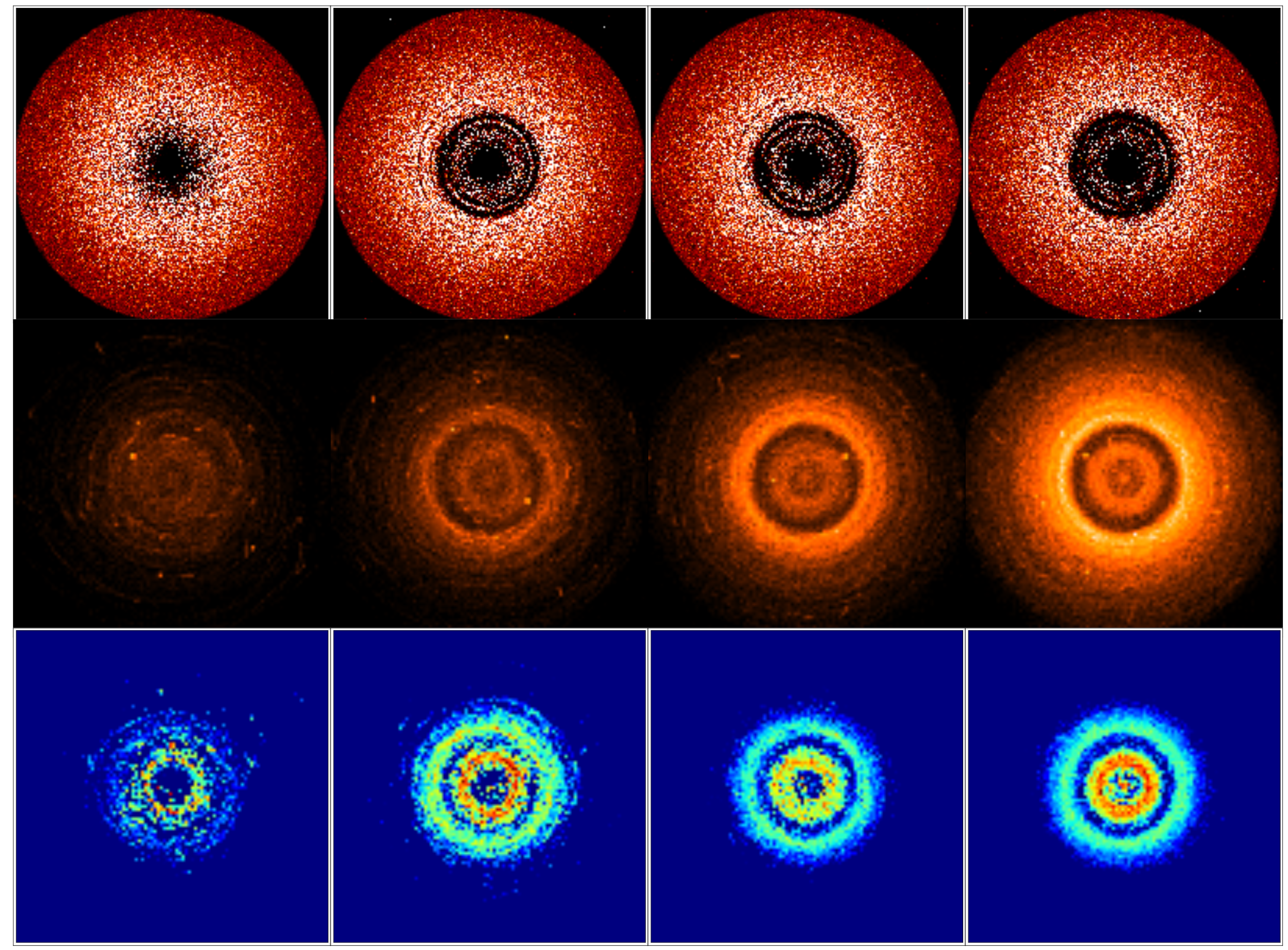
Follow Collision Fragments to Produce Dust Density Map

Dobinson et al., 2013

Surface Density

Dust Density

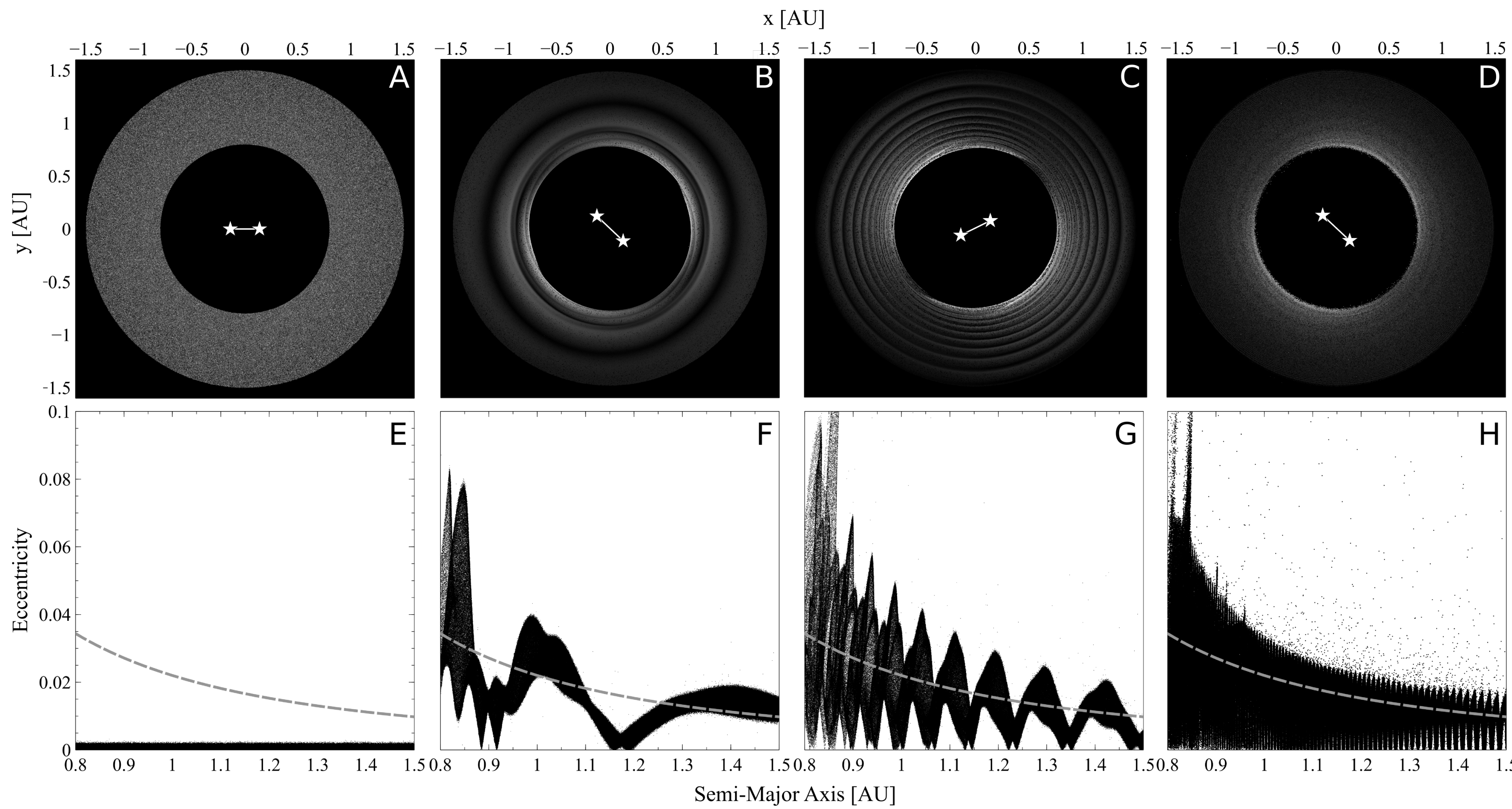
Radiative Transfer
10 μm



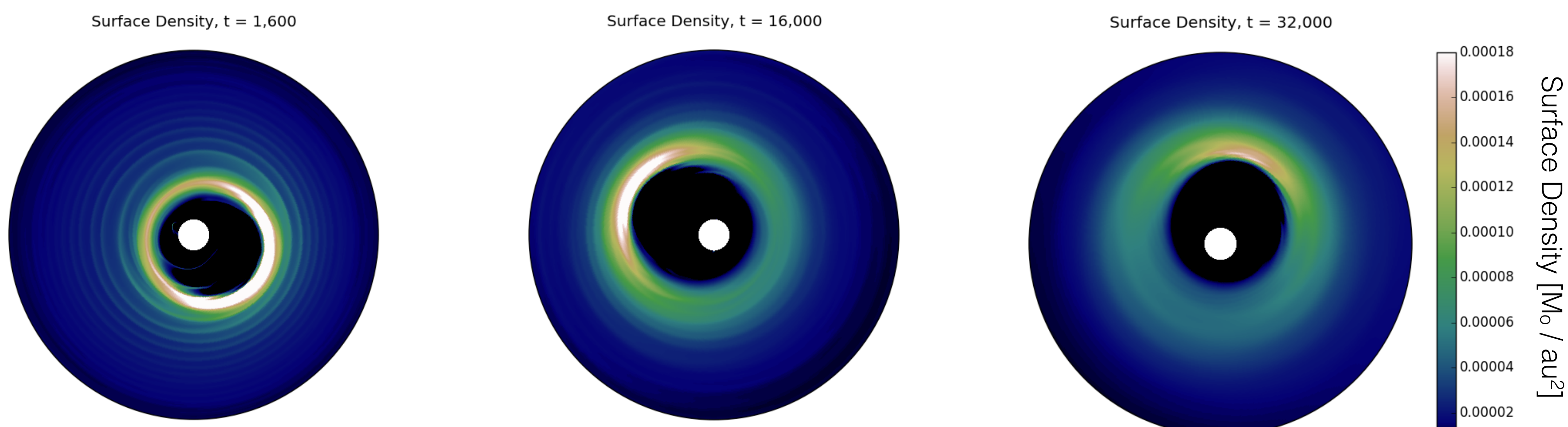
Dobinson et al., submitted
Dobinson et al., in prep

- Collisions between planetesimals are logged and re-simulated to produce fragments.
- 100 fragment tracers are used per collision and evolved as massless particles, with the star and planet as the only gravitating bodies.
- Radiative transfer modelling using RADMC3D at 10 μm shows what a telescope would see.

Circumbinary Planet Formation:
N-body & Hydrodynamical Simulations



Lines et al. 2014



Lines et al. in prep.