Perfect-SSDEM: A Hybrid N-body Collisional Model for Gravitational Collapse

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Gravitational collapse is a promising planetesimal formation mechanism

- Dynamical interactions between dust and nebular gas aggregates pebbles into localized, **gravitationally-bound clouds**[1,2,3]
- Cloud achieves critical density of pebbles, gas turbulence damped → **self-gravity dominates**
- **Cloud collapse** → pebbles accrete to form planetesimals O(10-100km)
- **Excess angular momentum** prevents the consolidation of pebbles into a single body → **binary planetesimal systems form**[4,5]
- **Bypasses planetesimal growth barriers** → pairwise growth prevents growth beyond m-sizes

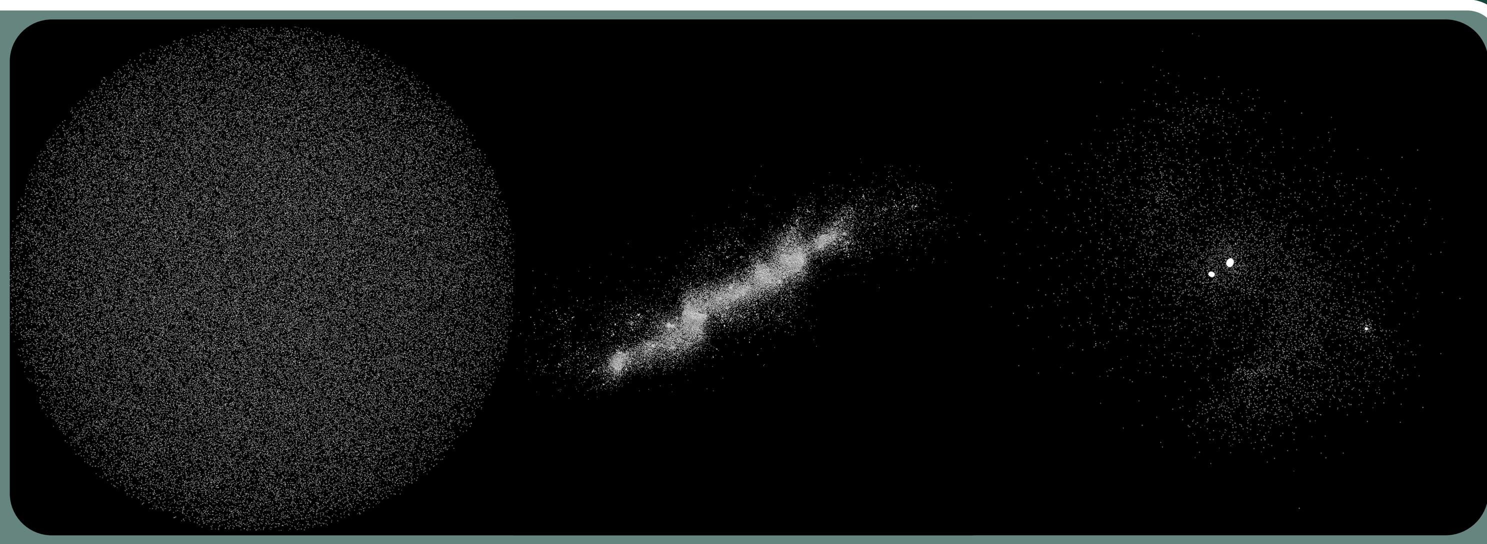

Fig. 1: Example of a model simulating gravitational collapse. Generated with PKDGRAV.

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A Super-particle Method to Model Collapse

- **Impossible** to directly simulate real clouds with **10^{21} pebbles**
- **Lower resolution analog clouds** can be used, with up to 10^5 **super-particles**[4,5]

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The Perfect-Merger Assumption

- **Idealized** collisional outcomes
  - Particles replaced by **new spherical particle** positioned at original particles' c.o.m. with c.o.m. velocity
  - **Perfectly inelastic** collisions → conserves incident particles' masses, volumes, and momentum
- Models use **inflated radii** to mimic the **high collision rate** of pebbles in a real collapsing cloud[4,5]
- **Can reproduce mass and orbits of pristine Kuiper Belt binary objects**[4,5]

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Motivation

To create a strong narrative of planetesimal formation, it is imperative to understand the mechanisms and initial conditions that drive the gravitational collapse process

The origins of planetesimal shapes and spins (e.g., relict Kuiper Belt objects) remain mysterious and have not been satisfactorily explained

We must understand the origin of planetesimals' shapes and spins, as these characteristics record their compositional, geophysical, and thermodynamic histories

Outstanding Issue in Modelling Gravitational Collapse

Models which have utilized perfect mergers during collapse[4,5] are able to match the reproduce the orbits of binary Kuiper Belt objects, but cannot properly examine planetesimal shapes and spins

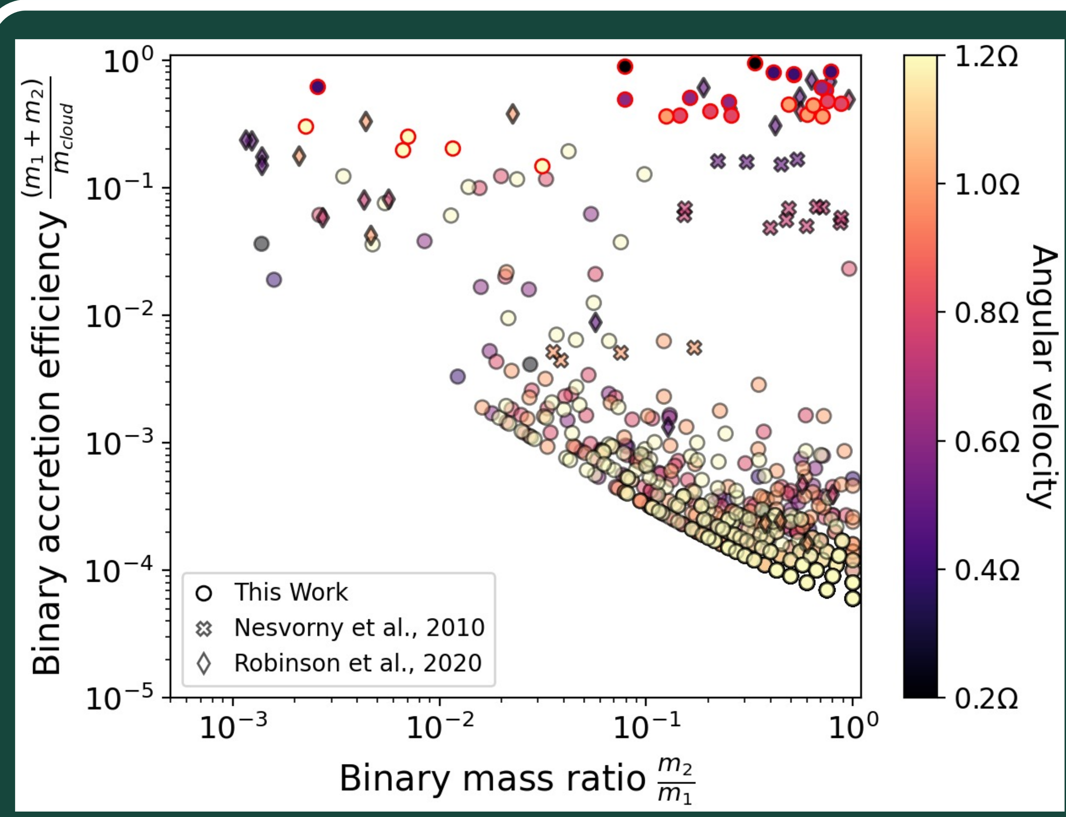

Fig. 3: Binary planetesimal accretion efficiencies and mass ratios over a range of initial cloud rotation states assuming solid-body rotation

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The Soft-sphere Discrete Element Method (SSDEM)

Can monitor planetesimal spins and shapes

- Particle **contact forces → particles rest upon one another**, no perfect mergers
- Planetesimals form as **particle aggregates**
- Track accretion and decretion
- **No artificial particle inflation**

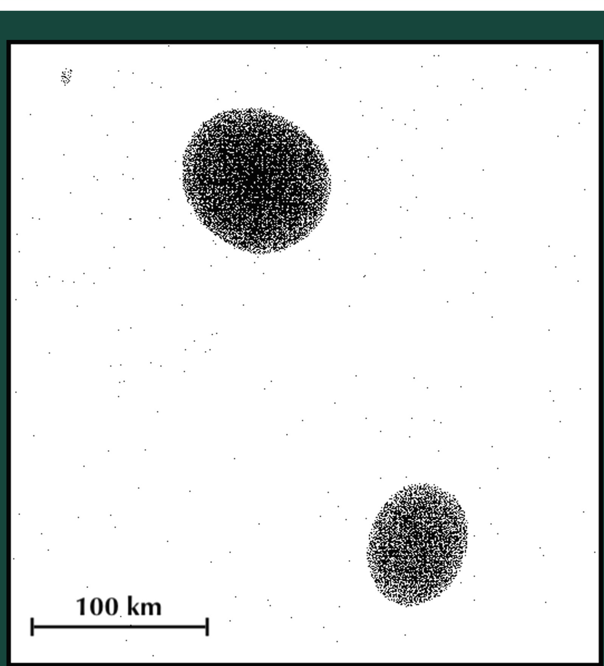

Fig. 2: An example of a binary system formed with the SSDEM

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Perfect-Merger vs. SSDEM

- SSDEM models produce binary planetesimal systems with masses and radii similar to perfect merger models *(Fig. 3)*
- **SSDEM notable differences:**
  1. Can track planetesimal **shapes** *(Fig. 2)* and **spins** *(Fig. 5)*
  2. Can form **tight binary orbits** → not precluded by inflated particle sizes *(Fig. 4)*

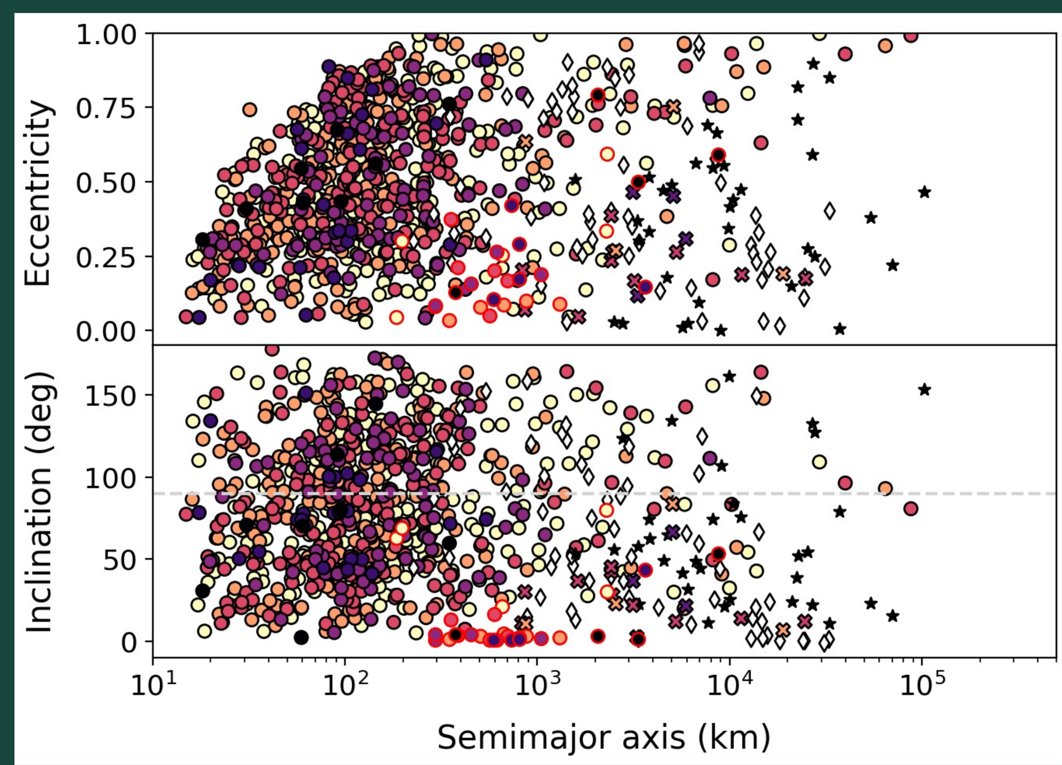

Fig. 4: The eccentricities and inclinations of binary planetesimal systems as a function of semimajor axes

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Modelling planetesimal formation via gravitational collapse requires a hybrid model

Perfect-mergers advantageous at the start of gravitational collapse when many collisions occur inflated particles are useful

The SSDEM advantageous at late stages of collapse when spins, shapes, and orbits begin to resolve

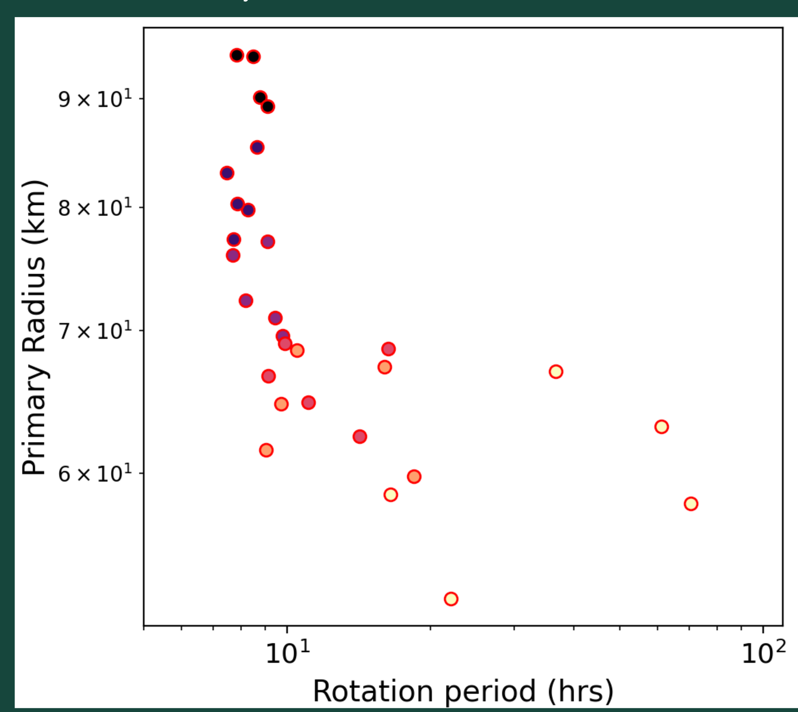

Fig. 5: Primary planetesimal radii vs. rotation period

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The "Perfect-SSDEM" hybrid N-body model

Clouds contain super-particles with unrealisitically low densities that transition into particles with realistic densities

- **Two distinct particle types:**
  1. **Cloud-particles** – Imitate clouds of real particles as individual super-particles – use **perfect-merging**
  2. **Aggregate-particles** – Represent individual real particles as in an SSDEM model, with realistic densities (1 g/cm^3) – use **contact physics**
- **Clouds initially composed of cloud-particles**
  - Cloud-particle cross-sections modified as collisions occur
- Cloud particles **transition into aggregate-particles** upon achieving a **threshold mass**
- **Collisions between aggregate-particles and cloud-particles** determined by a pair of cut-off masses around the transition mass
  - **Two possible collisional outcomes:**
    1. Growth of aggregate-particle by the mass of the cloud-particle
    2. Creation of a new aggregate-particle out of the cloud-particle
- Cloud-particles that rarely or never collide remain cloud-particles → not mistaken for a bound planetesimal or satellite → remain debris

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Key Takeaway

The Perfect-SSDEM model will be able to create planetesimals as aggregates with both shape and rotational properties, while effectively modelling the large number of collisions that may theoretically take place in a real pebble cloud.

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