`gadgetbelt`: a tool for modeling planetary sculpting of massive debris disks

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Introduction

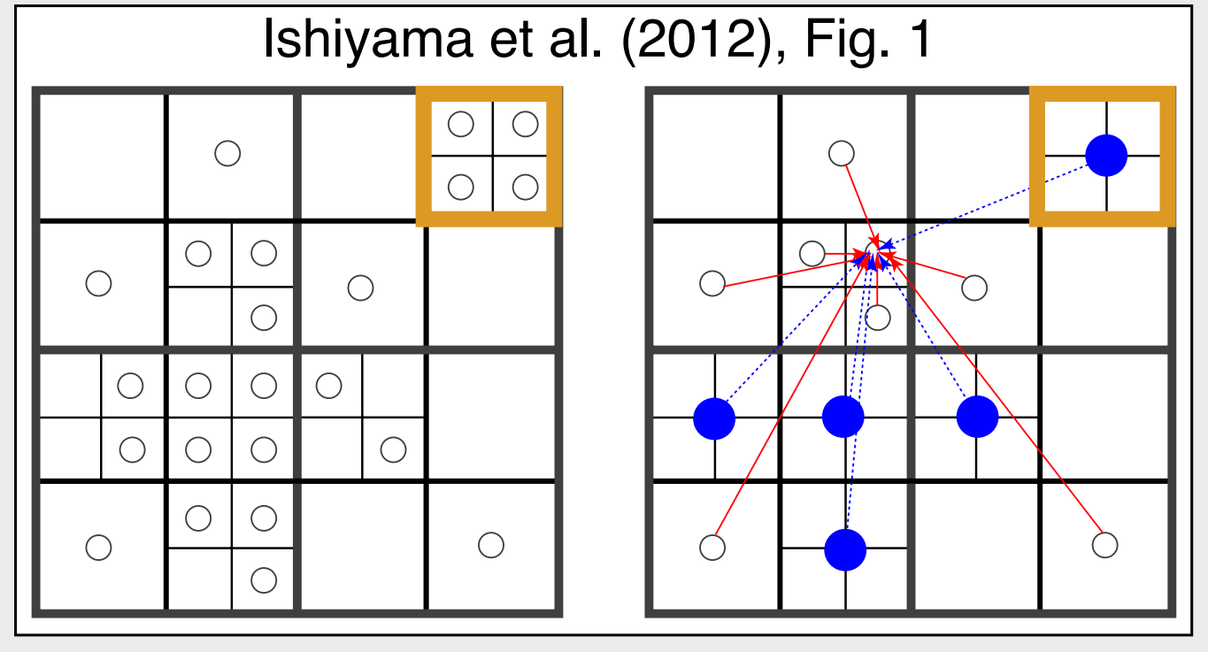
In models of the sculpting of planetesimal disks by planets, the planetesimals are often treated as test particles, with their effects on the planet modeled analytically. However, this treatment is insufficient in regimes in which: 1) the disk's self-gravity cannot be neglected (i.e. early in the disk's lifetime, it may have mass comparable to the sculpting planet), and/or 2) the back-reaction on the planet by a large number of small planetesimals must be simulated (e.g. for modeling stochastic effects). We are adapting `gadget` (Springel 2005), a cosmological simulation code, for use in non-collisional debris disks, allowing us to model thousands to millions of planetesimals in a reasonable CPU time through gains in speed from gadget's parallel processing implementation and tree code for N-body interactions. We will use this adaption, `gadgetbelt`, to explore planet-disk interactions in regimes in which the debris disk's mass is comparable to that of the planet.

Development and benchmarking

Treatment of gravitational forces

Gravitational tree algorithm

Ishiyama et al. (2012), Fig. 1

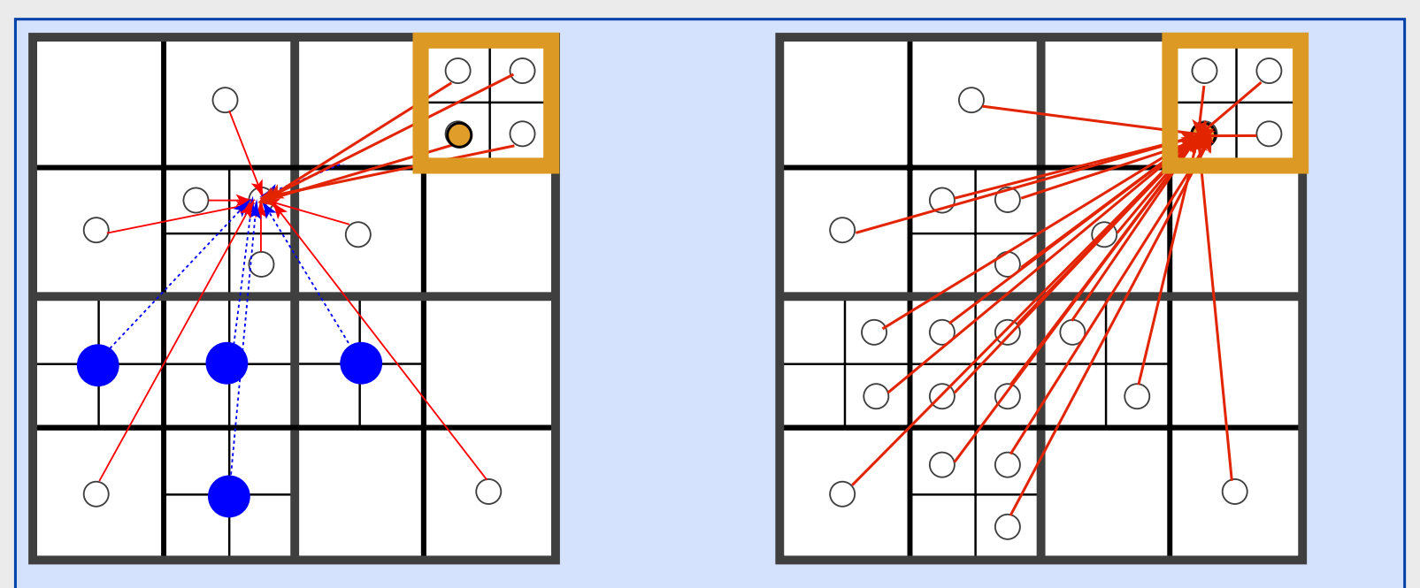


Particle layout

Forces on a particle. Distant particles are combined into nodes.

○ particle
● node
→ particle force
⇢ node force

Our modified implementation

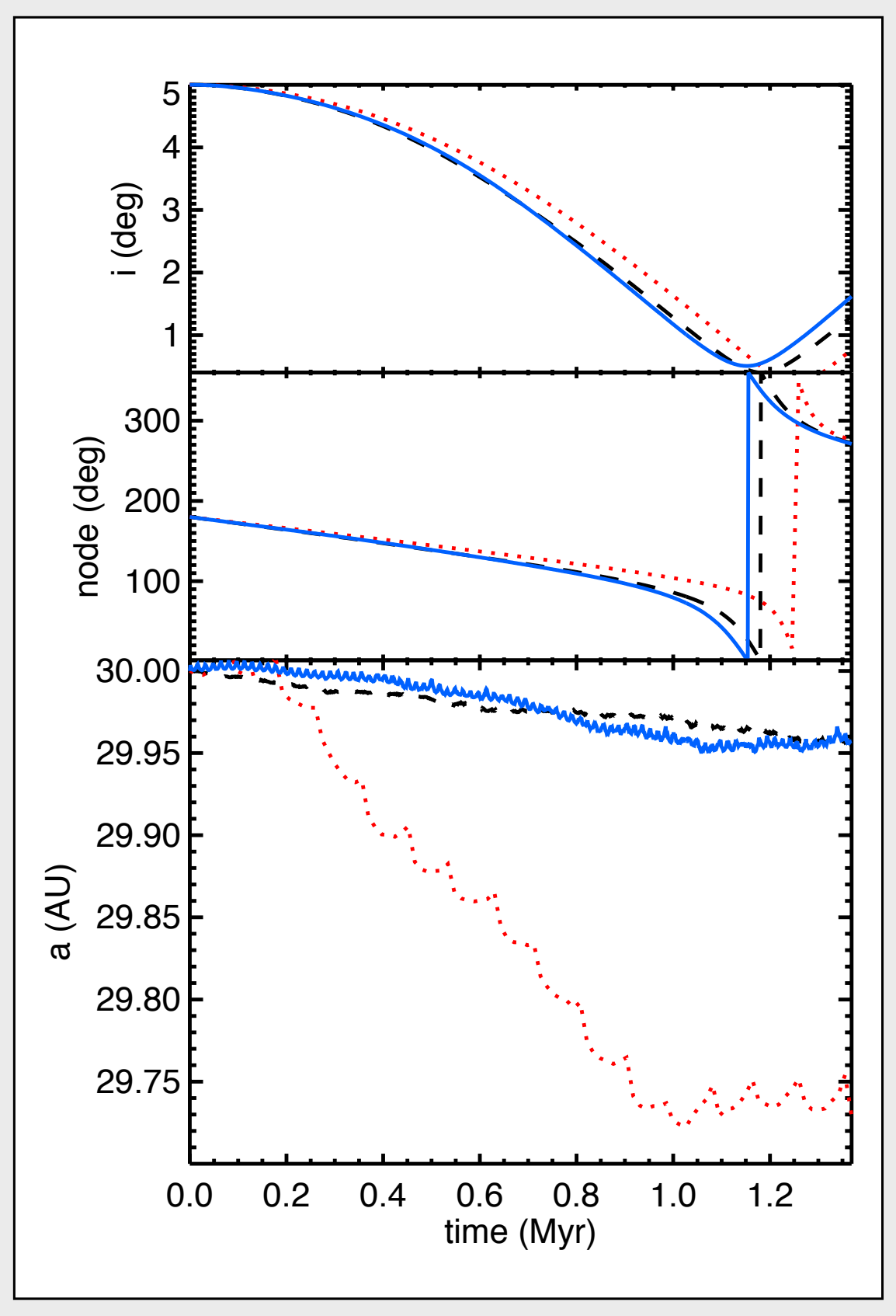


Forces on a planetesimal. Computed using tree except force by planet calculated directly.

Forces on a planet. All calculated directly.

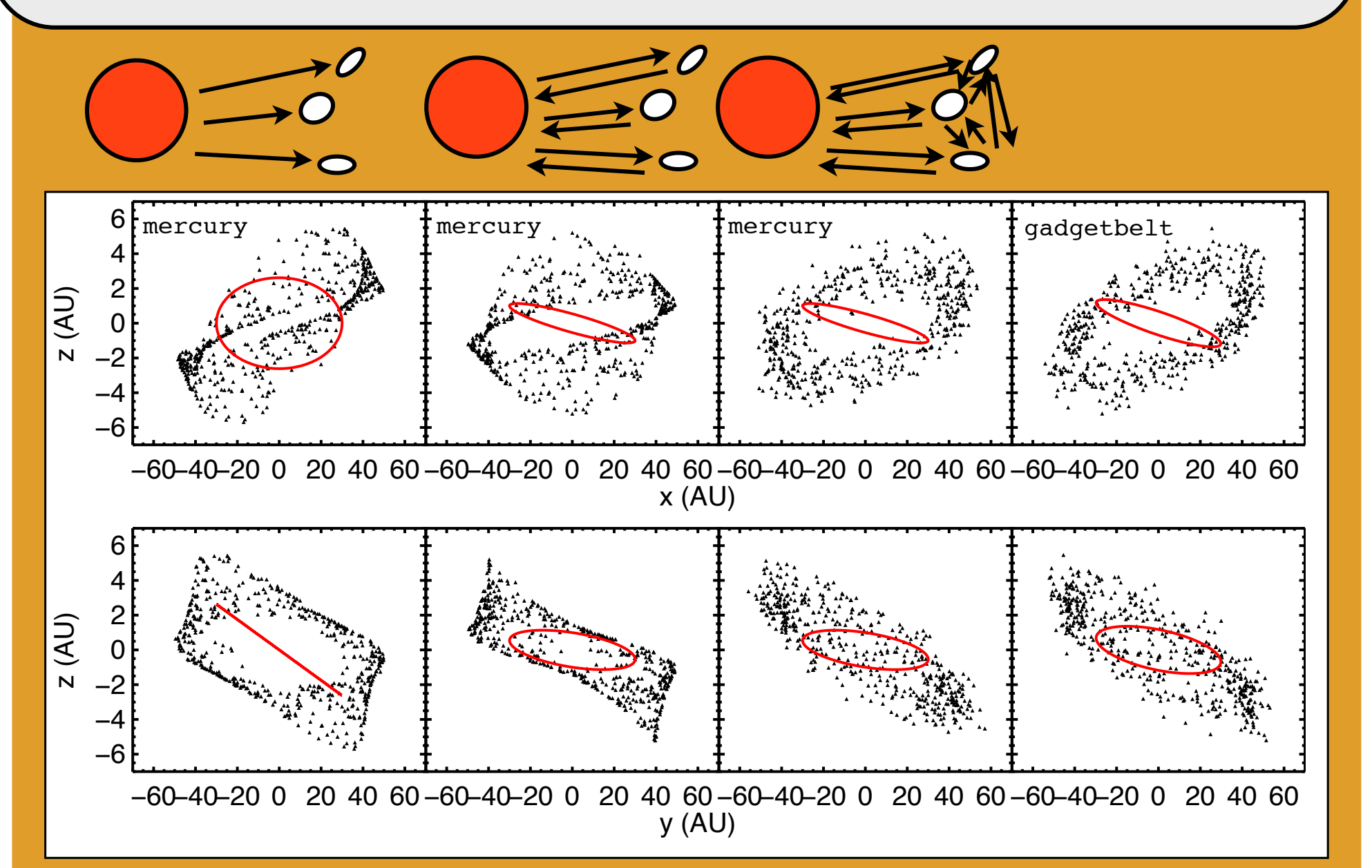
○ planetesimal particle
● planet particle

We retain the gravitational tree algorithm for planetesimal-planetesimal interactions but compute the forces exerted on and by the planet directly. To do so, we implement a cell-opening criterion in which every cell is opened when computing the forces on the planet and in which the cell containing the planet is always opened. The figure on the left reveals discrepancies between the full gravitational treatment using `mercury` and the approximate treatment using the unmodified version of `gadget`. Numerical stochasticity causes the planet to random walk with larger steps, resulting in a large net migration. The change in the planet's semi-major axis in turn changes the secular evolution timescale, resulting in a different period for the precession of the planet's node and the oscillation of its inclination.



Evolution of the inclination (top), longitude of ascending node (middle), and semi-major axis (bottom) of an inclined, Neptune-mass planet interacting with an exterior, Neptune-mass planetesimal belt, simulated using `mercury` Bulirsch–Stoer (Chambers 1999, black dashed line), unmodified `gadget` (Springel 2005, red dotted line), and modified `gadgetbelt` (blue solid line). Without (red dotted line) modifications, the planet undergoes a more stochastic random walk that alters the evolution timescale is its inclination and node.

Example: warped disk



Two viewing angles (top and bottom) of planetesimals' instantaneous positions (black) and planet's orbit (red) for different gravitational treatments (columns). Columns 1-3 employ the `mercury` Bulirsch-Stoer integrator (Chambers 1999) for benchmarking with `gadgetbelt`. Column 1: planetesimals treated as test particles (appropriate for disk masses << planet, e.g. Beta Pictoris, Dawson et al. 2011) . Column 2: planetesimals treated as "small bodies" (interact with planet but not each other). Column 3: full gravitational treatment. Column 4: Modeled in `gadgetbelt`.

A 20 MEarth inclined planet orbit warps a 20 MEarth planetsimal disk. Planetesimals back-react on the planet, alter its orbit, and self stir.

Computational efficiency

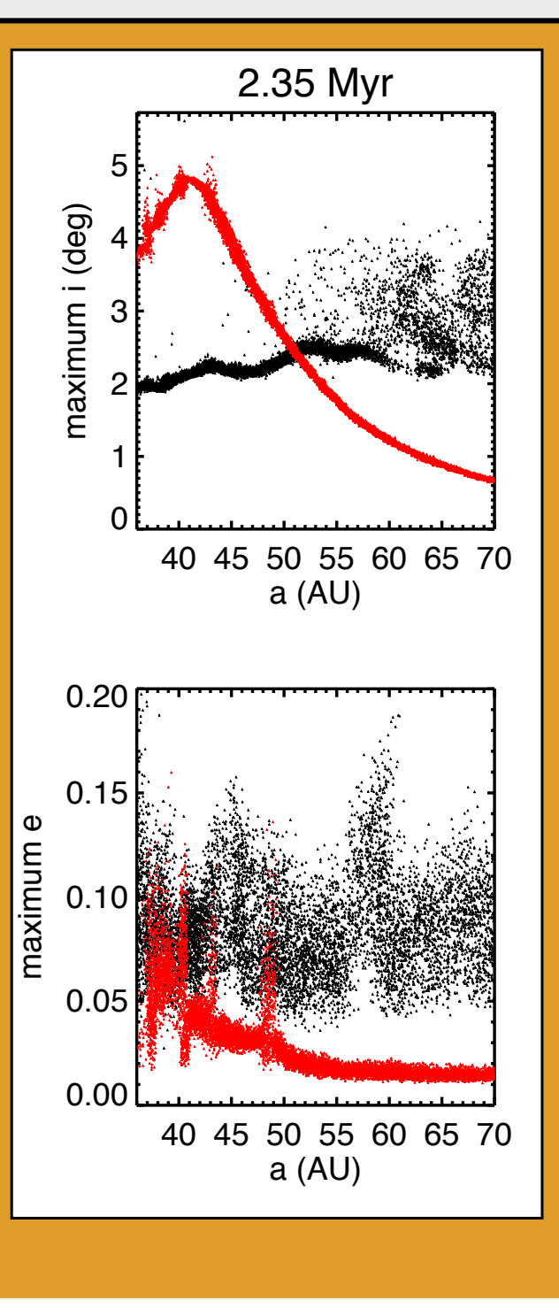
We are exploring the computational efficiency of the `gadgetbelt`, including how the computation time scales with the number of processors. 20 MEarth corresponds to one million 500-km planetesimals.

Gravitational softening

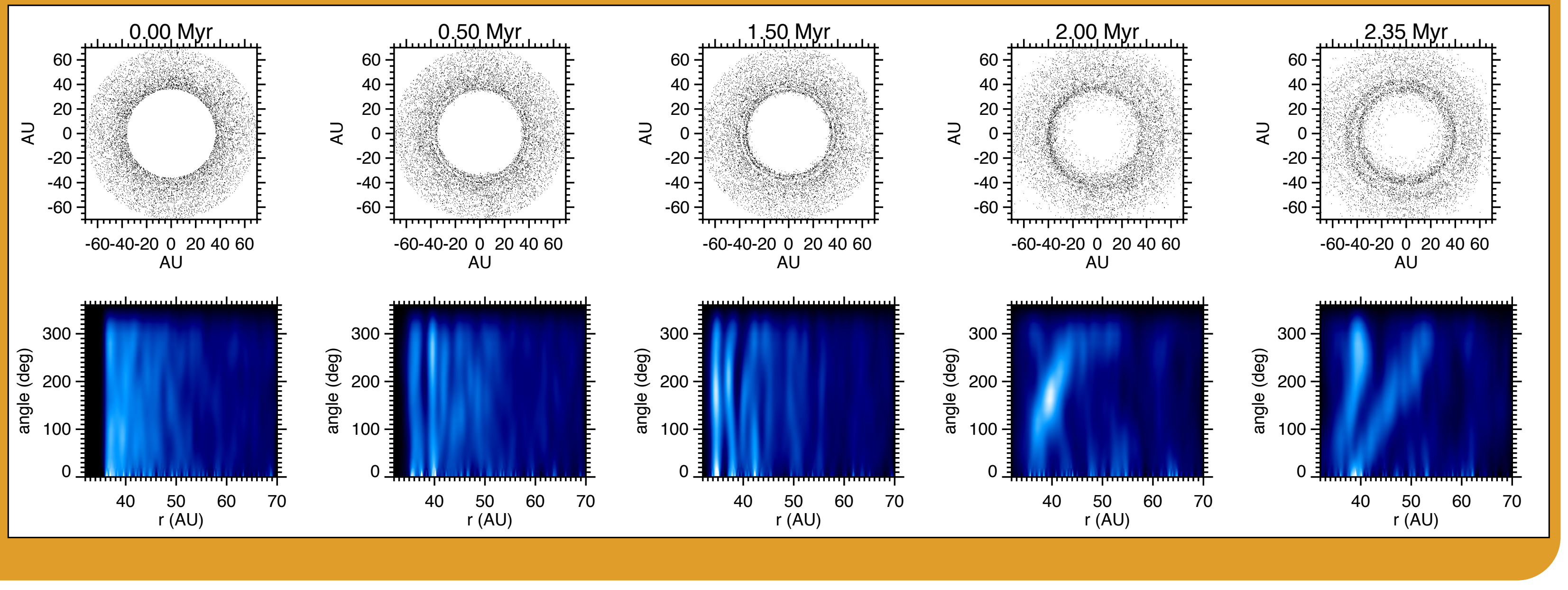
We are optimizing the gravitational softening (smoothing) parameter that also sets the maximum timestep. In the regimes we are exploring, it is not necessary to follow close encounters among planetesimals.

Example: density waves

In a self-gravitating disk, density waves propogate, launched at the disk edge or at resonances. In the latter case, density waves can smear out the excitation of eccentricities and inclinations caused by secular resonances, as explored by Hahn (2003) using the ring approximation.



Left: Planetesimals in a 10 MEarth (black) and 0.0001 MEarth (red) Kuiper belt, modeled with `gadgetbelt` including solar system planets. Top: Density waves smear out the excitation caused by the nu8 secular resonance. Bottom: Planetesimals' self-gravity stirs up the disk and alters excitation caused by mean motion resonances.



Below: Spiral density waves propagate through a 10 MEarth disk [initial density profile proportional to a^(-1.5)]. Top: planetesimal positions, modeled with `gadgetbelt` including solar system planets.. Bottom: Contoured, smoothed surface density as a function of polar angle and radius.

Future Work

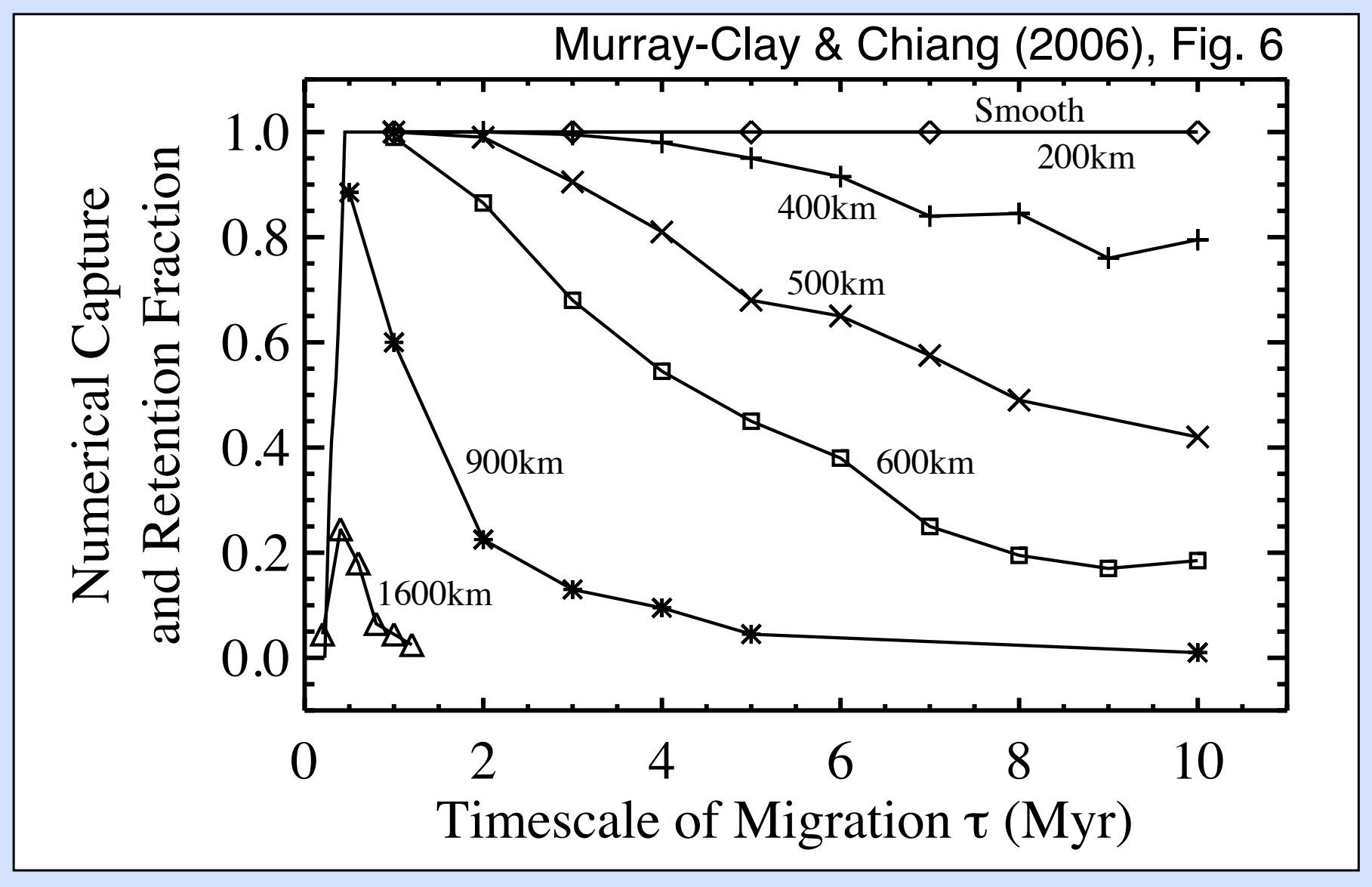
Code development and benchmarking

-- Implementation of a higher-order symplectic integrator for planet particles
-- Assessment of computational efficiency
-- Optimization of gravitational softening parameter
-- Implementation of artificial collisional damping force and other user-defined forces

Applications

Stochastic migration

Murray-Clay & Chiang (2006), Fig. 6



Murray-Clay and Chiang (2006) developed analytical models for the stochasticity of planetesimal driven migration, caused by the finite size of Kuiper belt objects (KBOs) entering a planet's hill sphere, and a test of the planetesimal size distribution based on today's population of resonant KBOs, but it was not computationally feasible to combine stochastic migration with N-body models of the global dynamics of the Solar System. We will place constraints on the early planetesimal size distribution through global N-body simulations of early Solar System that include both the planetesimal disk and stochastic migration.

Planetary sculpting of debris disks

Previously, we performed a parameter study of Kuiper belt assembly (Wolff et al. 2012, Dawson and Murray-Clay 2012), in which we modeled the KBOs as massless test particles. We will investigate for which masses of the planetesimal disk the constraints we developed hold, accounting for the back-reaction of the disk and self-gravity.

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