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Ultra-High Resolution Simulations of Planetary Collisions

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Motivation

- **Giant impacts (GI)** form the last stage of planet formation and play a key role in determining many aspects (e.g., structure of planetary systems, masses and compositions of its constituents, presence of regular satellites). Understanding the outcome of such collisions is crucial for understanding the formation and evolution of planetary systems.
- A common choice for numerically solving the equations of motion is the **Smoothed Particle Hydrodynamics (SPH)** method. Due to its Lagrangian nature, SPH can accurately model large deformation of the bodies during the collision and track the origin of the material which makes it well suited for studying GI.
- Prior work investigating GI was limited in resolution due to computational constraints. Since in SPH, the resolution follows the mass, low mass structures like circumplanetary disks, planetary crusts, oceans, and atmospheres are poorly resolved at currently achievable particle numbers.

The Code

- We present a new **SPH code** that is built into the modern gravity code **pkdgrav3**[1].
- Our implementation is a fully conservative and self-consistent SPH formulation with ∇h terms to correct for variable smoothing lengths[2].
- The code was adapted to simulate GI with the addition of an interface/surface correction[3] to correct the density estimate at material and vacuum interfaces, where the standard SPH density estimator results in erroneous or even unphysical states.
- In order to accurately conserve entropy in the absence of shocks, the PdV work in the energy equation can be replaced by an isentropic evolution (ISPH)[4].
- A generalized Equation of State (EOS) interface allows the use of various material prescriptions. Currently available are the ideal gas and EOS for the typical constituents of planets: rock, iron, water, and hydrogen/helium mixtures.
- Time integration is done with individual and adaptive particle time steps using the symplectic Kick-Drift-Kick (KDK) leapfrog scheme with embedded predictor-corrector.

Performance

- The gravity code uses the Fast Multipole Method (FMM) on a distributed binary tree to achieve $O(N)$ scaling.
- The code is designed to use modern hardware: it uses SIMD vectorization and, if present, GPUs to perform most of the floating-point operations.
- On-node parallelization is done using pthread threads while the communication between nodes relies on the Message Passing Interface (MPI).
- Neighbor finding in SPH is done for a whole group of particles at once and is tightly coupled to the FMM tree code so that only one tree walk is performed per group. The SPH implementation therefore preserves the O(N) scaling of the gravity code.
- The performance on Piz Daint CPU nodes (2x18 CPU cores per node) is shown in Figures 1 – 3.

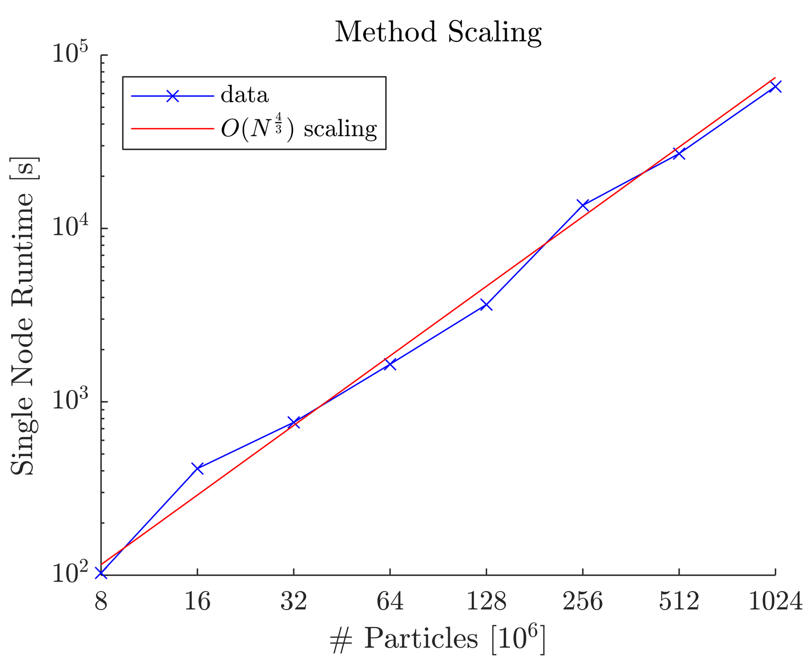

Figure 1: The runtime for a step on a single Piz Daint CPU node follows closely the expected scaling that results from the scaling of the runtime per substep and the scaling of the number of substeps given by the CFL condition.

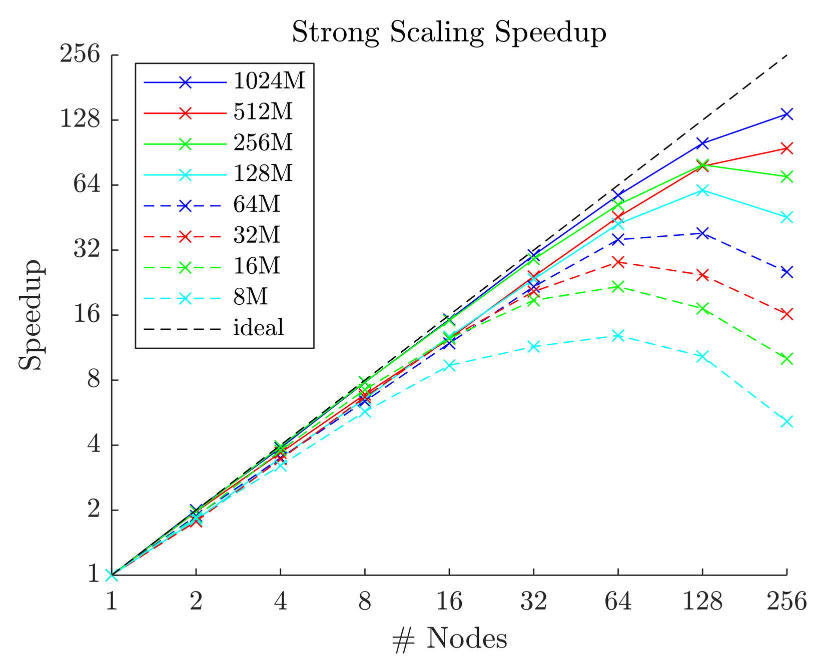

Figure 2: Strong scaling results on Piz Daint CPU nodes for different resolutions. The number of particles in the simulation is given by the legend entry. With increasing particle number, the strong scaling gets better. The increase is not monotonic due to differing occupation of the smallest timestep, where low occupancy can hamper the scaling.

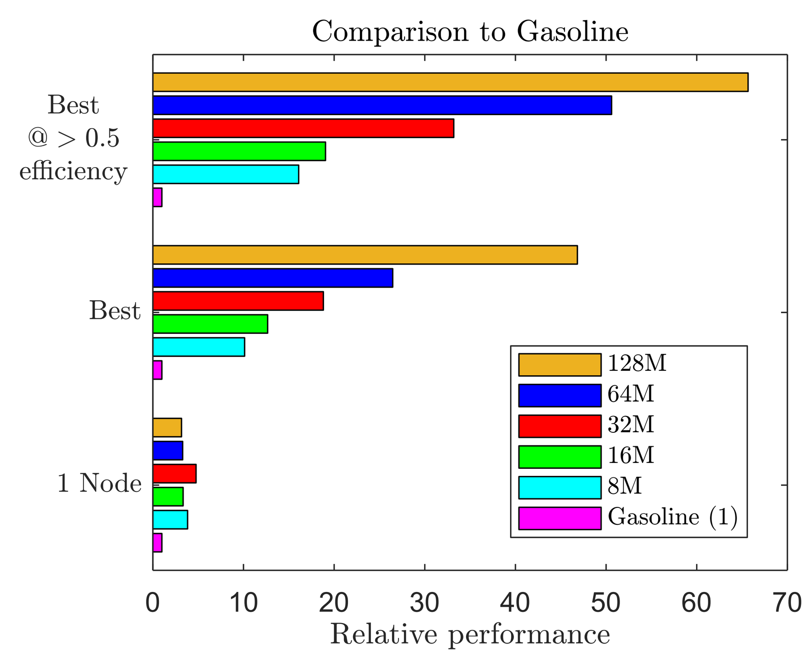

Figure 3: Performance comparison to the predecessor code Gasoline[4,5,6] on Piz Daint CPU nodes. Gasoline wallclock is normalized to 1. Speedup on a single node is between a factor of 3 and 5, but when scaled out to 50% parallel efficiency, pkdgrav3 is up to 65 times faster than Gasoline.

Applications

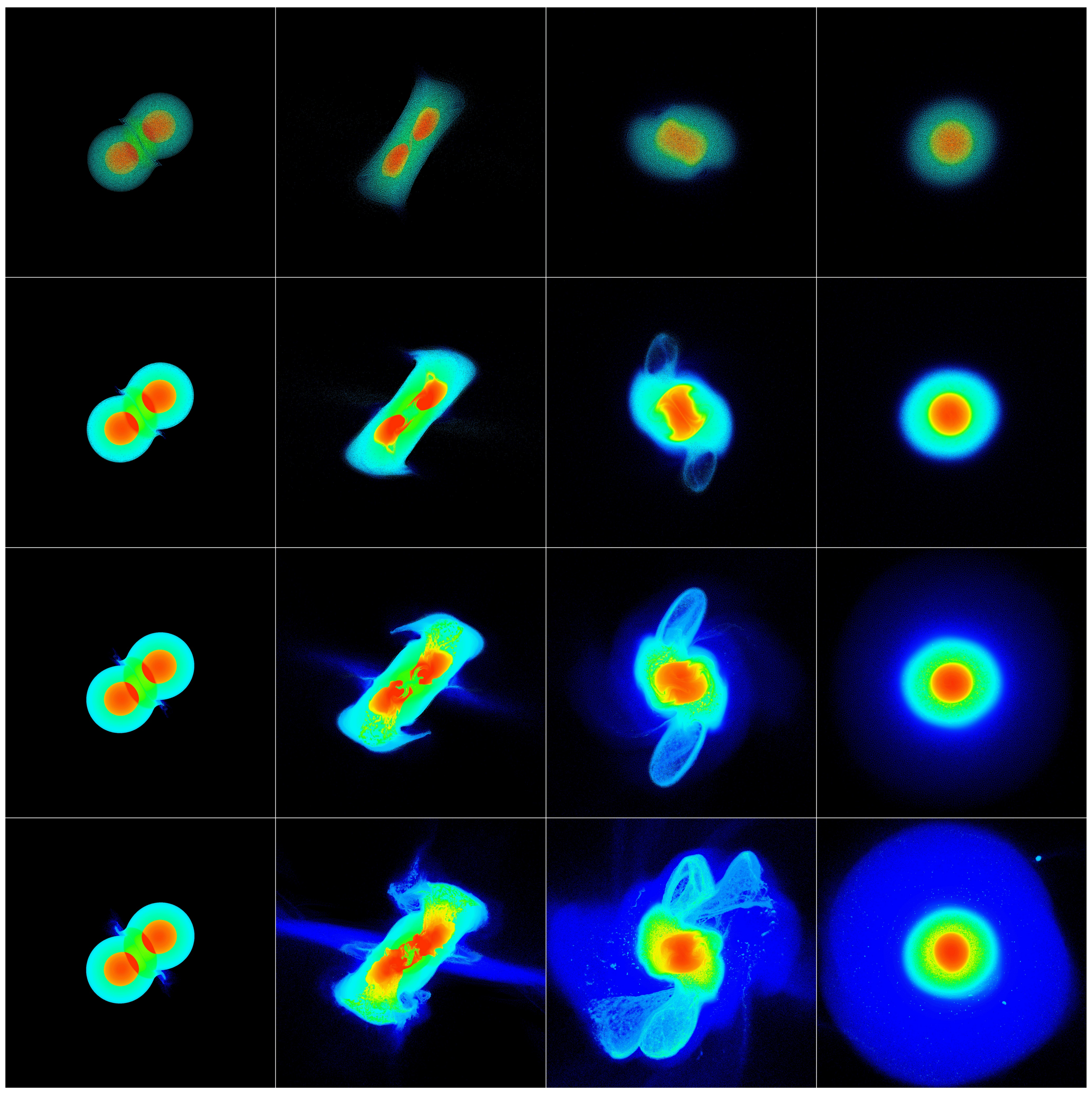

Figure 4: The projected density distribution (0 g/cm³ (blue) to 14.4 g/cm³ (red)) of a collision between two Earth-analogues with different resolution (from top to bottom: 2×10^5, 2×10^6, 2×10^7 and 2×10^8 particles) is shown at different times (from left to right: 10min, 106min, 5.3h and 17.7h after the collision). With increasing resolution, more features (e.g., the spiral arms) appear in the simulation. This has a visible impact on the angular momentum distribution and results in a lower rotation of the merged cores.

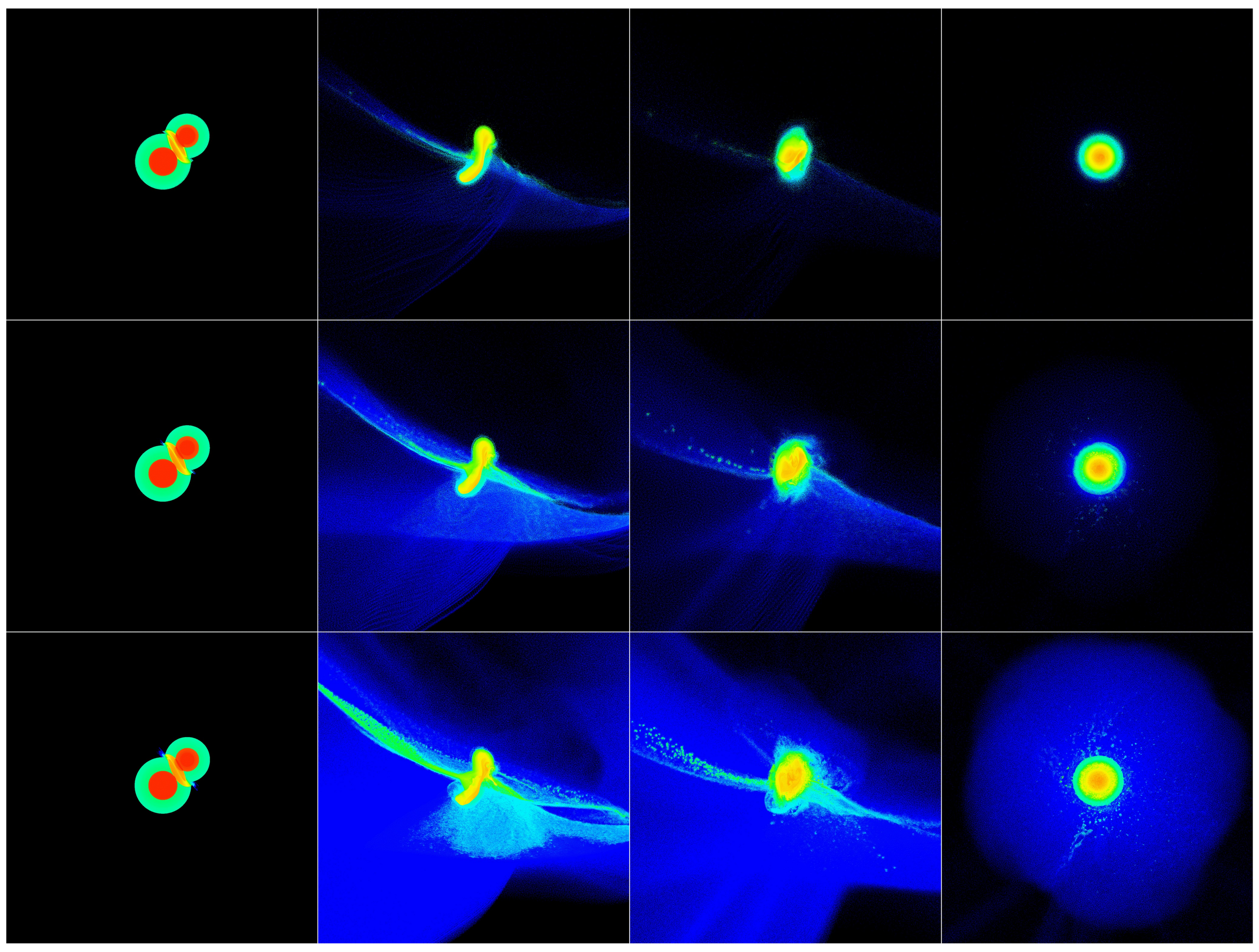

Figure 5: A collision that substantially alters the composition of the target by stripping the mantle to form a Mercury-like planet with a huge iron core[7]. The projected density distribution (0 g/cm³ (blue) to 9 g/cm³ (red)) for different resolutions (from top to bottom: 1.5×10^6, 1.5×10^7 and 1.5×10^8 particles) is shown at different times (from left to right: 2min, 106min, 3.5h and 35.4h after the collision). With increasing resolution, more substructure is revealed in the infalling material, and the fluid becomes more turbulent, promoting mixing between the iron core and the silicates in the final body.

Outlook

- Future improvements to the physics capabilities of the code will include state-of-the-art artificial viscosity (AV) limiters, an artificial thermal conductivity which further increase mixing at material interfaces and a material strength formulation.
- Performance will be further improved by adding GPU support for all features.

References:
[1]Potter et al. 2017, Comput. Astrophys. 4, 2
[2]Springel & Hernquist 2002, MNRAS 333, 3, 649-664
[3]Ruiz-Bonilla et al. 2022, MNRAS 512, 3, 4660-4668
[4]Reinhardt & Stadel 2017, MNRAS 467, 4, 4252-4263
[5]Wadsley et al. 2004, New Ast. 9, 2, 137-158
[6]Reinhardt et al. 2020, MNRAS 492, 4, 5336-5353
[7]Chau et al. 2018, ApJ 865, 35

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