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A New GPU-based Approach to Visualizing Dark Matter Simulations

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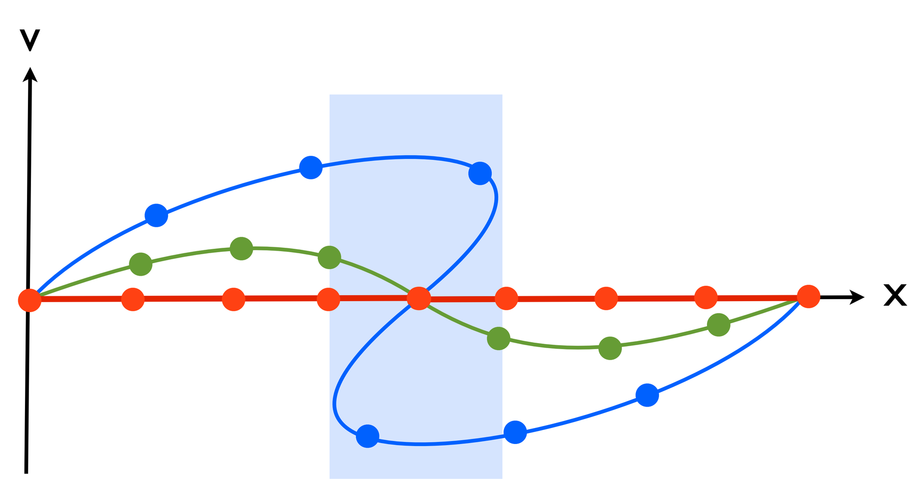
Summary

In the last decades cosmological N-body dark matter simulations have enabled ab initio studies of the formation of structure in the Universe. Gravity amplified small density fluctuations generated shortly after the Big Bang, leading to the formation of galaxies in the cosmic web. These calculations have led to a growing demand for methods to analyze time-dependent particle based simulations. Rendering methods for such N-body simulation data usually approximate the spatial distributions of physical quantities using kernel interpolation techniques, common in SPH (smoothed particle hydrodynamics)-codes.

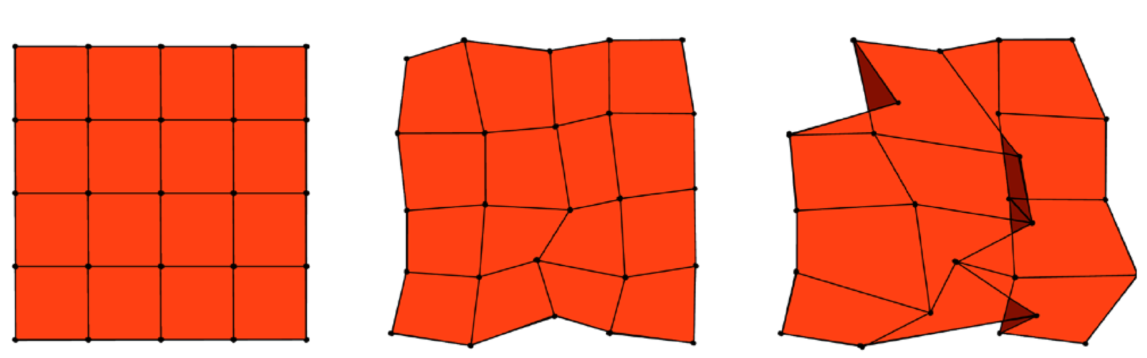
We present a GPU-based rendering approach, based on a new, accurate method to compute the physical densities of dark matter simulation data. It uses full phase-space information to generate a tetrahedral tessellation of the computational domain, with mesh vertices defined by the simulation's dark matter particle positions. Over time the mesh is deformed by gravitational forces, causing the tetrahedral cells to warp and overlap. The new methods are well suited to visualize the cosmic web. In particular they preserve caustics, regions of high density that emerge, when several streams of dark matter particles share the same location in space, indicating the formation of large-scale structures, like sheets, filaments and halos.

Method

At early times, the dark matter fluid is almost uniformly distributed and at rest, as depicted by the red line in the Figure below. Over time, gravity accelerates the dark matter fluid elements and they gain velocity, denoted by the green line. At later times different streams of dark matter co-exist in the same spatial regions, in this example there are three regions per spatial location for elements on the blue line inside the transparent box. These so-called multi-stream regions provide important information about the formation of structures in the dark matter distribution on large spatial scales.

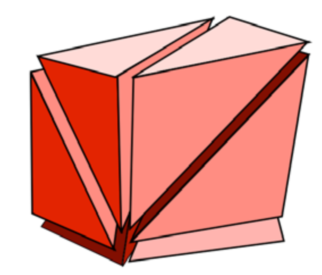


Given a time-dependent 3D N-body dark matter simulation, a tetrahedral mesh is constructed, with a connectivity implicitly defined by the layout of the tracers on a regular grid at the initial time-step, which can be reconstructed at any time step from the tracer's unique IDs. The same amount of mass is assigned to each tetrahedral element and derived quantities, like time-dependent mass densities, are computed based on the volumes of all tetrahedral elements that overlap a certain location. The mass is associated with the cells and not the vertices of the tessellation. The nodes of the mesh are updated over time, according to the tracer's actual position, changing the volumes and thus the spatial mass densities. The tessellation has consistent vertices, edges and faces for abutting cells, and in particular does not contain any dangling nodes, but at later times the tetrahedral elements will typically start to overlap.

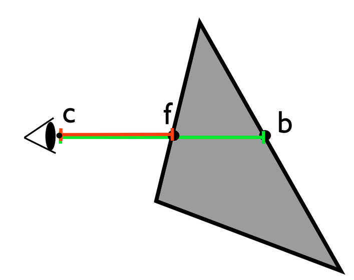


GPU Implementation

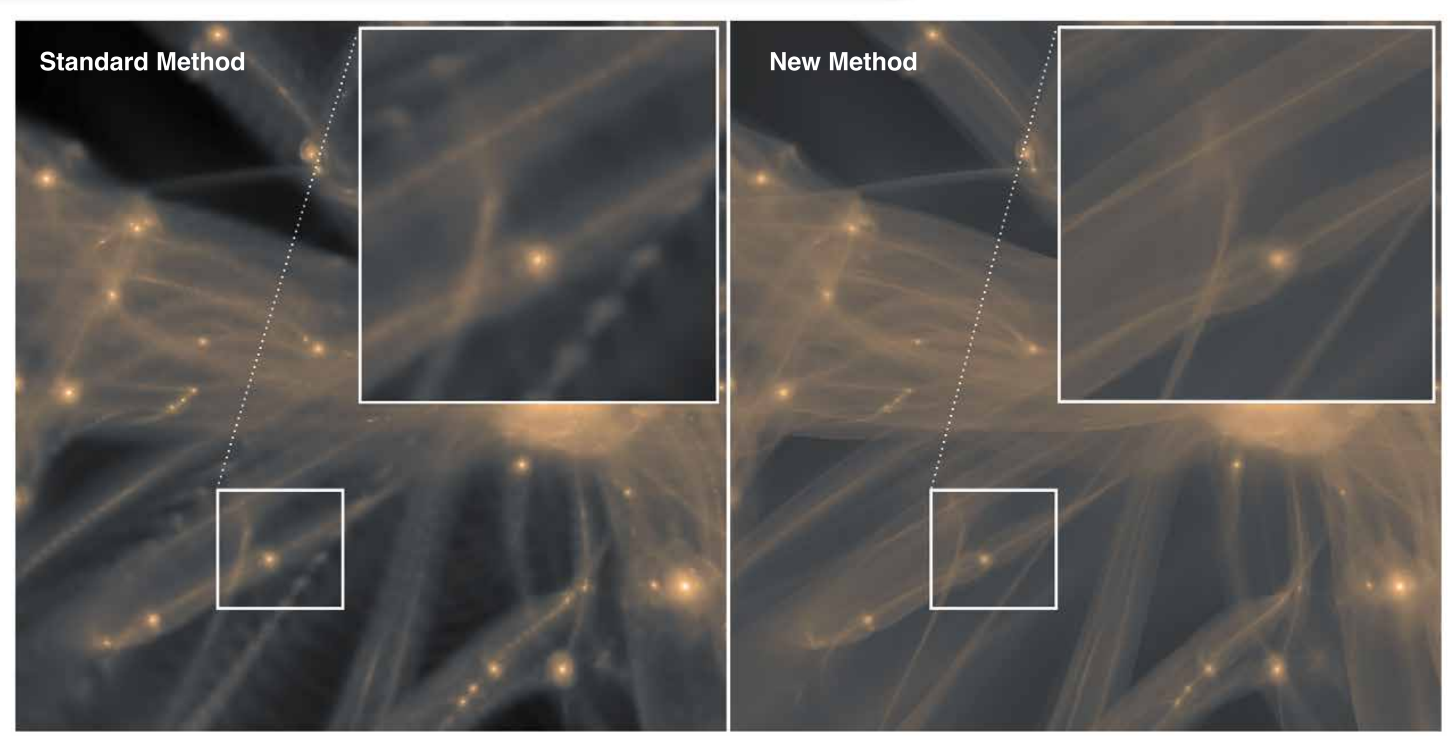
The special nature of the initial conditions allows for a very memory efficient representation of the mesh on the GPU, without the need to store and transfer any explicit connectivity information or additional attributes about the tetrahedral cells, except for the positions of the tracer particles. All connectivity and derived information, like the volumes and mass densities of the tetrahedral cells, are generated on-the-fly on the GPU in OpenGL shaders.



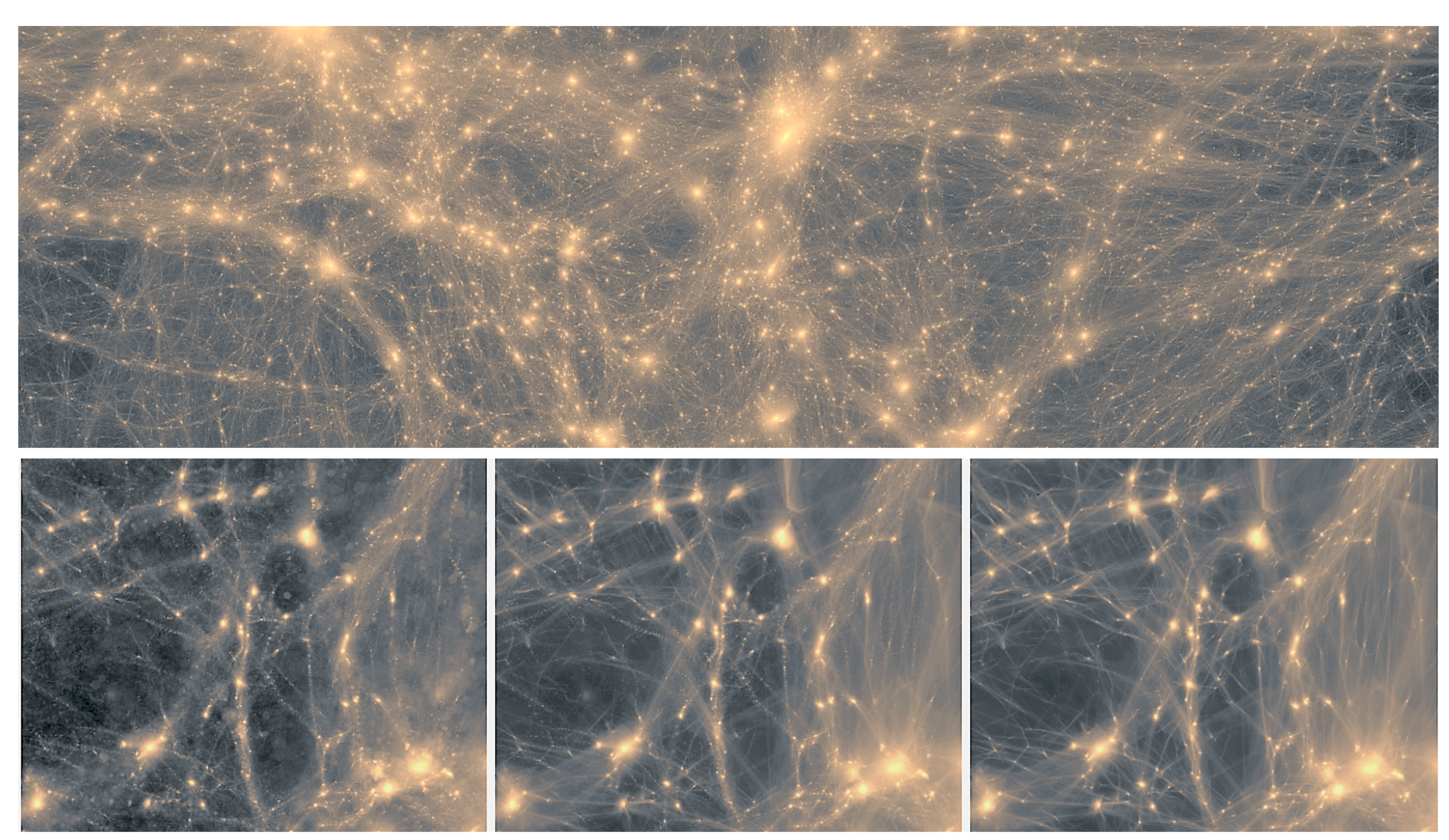
The tracer particle positions are stored in a three-dimensional floating-point texture, enabling the access and sampling of the cell vertices in the vertex shader. The instance counter (gl_InstanceID) determines which tetrahedral elements are processed and the particle positions are obtained from the position texture and processed in the geometry shader. Here the six (deformed) tetrahedra are constructed, based on the current tracer positions, and the mass as well as the volume for each tetrahedron is computed on-the-fly. A cell-projection approach in the fragment shader is used to compute the accumulated projected densities in the image plane.



Results

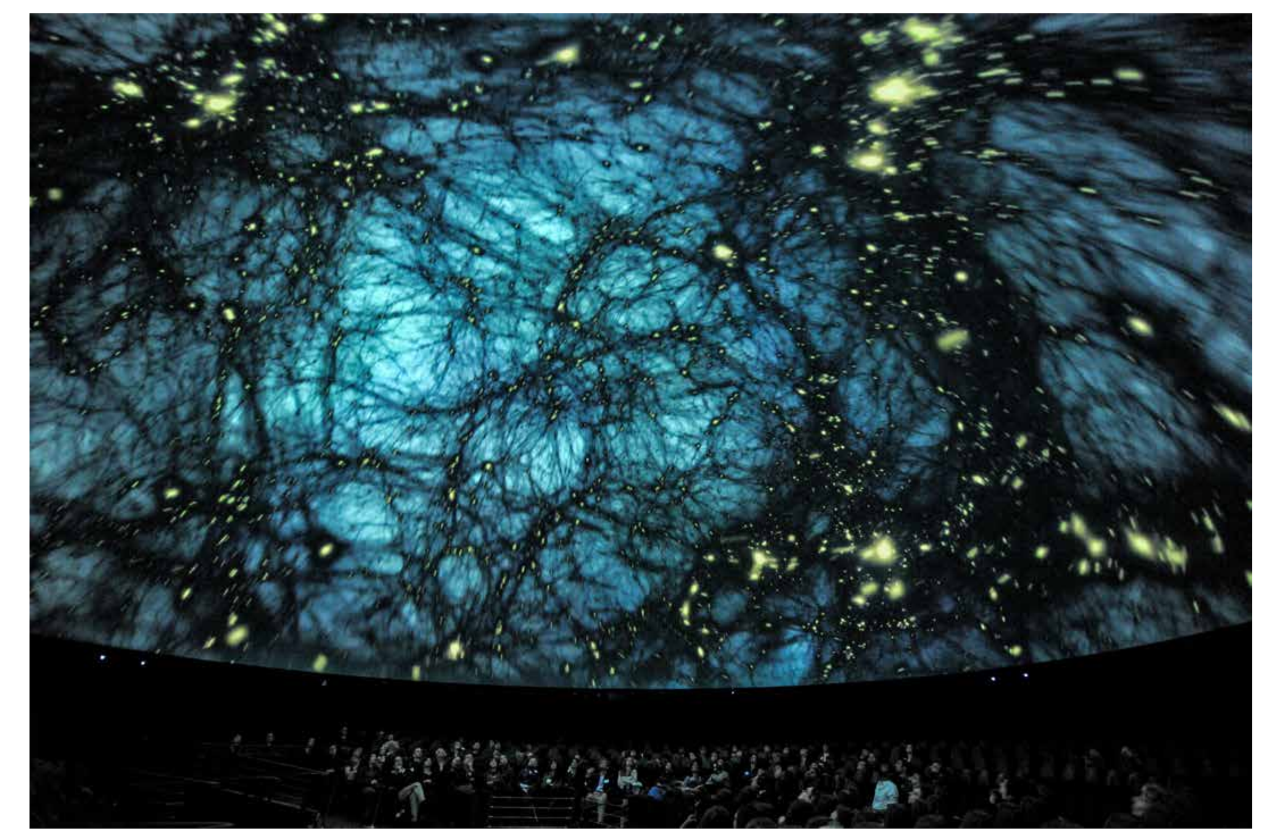


A direct comparison between a standard SPH adaptive kernel smoothing method (left) and our tetrahedral cell-projection approach (right). Artifacts due to the poor density estimates in low-density regions are obvious for the SPH method, whereas the tetrahedral approach achieves an overall high image quality, both on small and large structures.

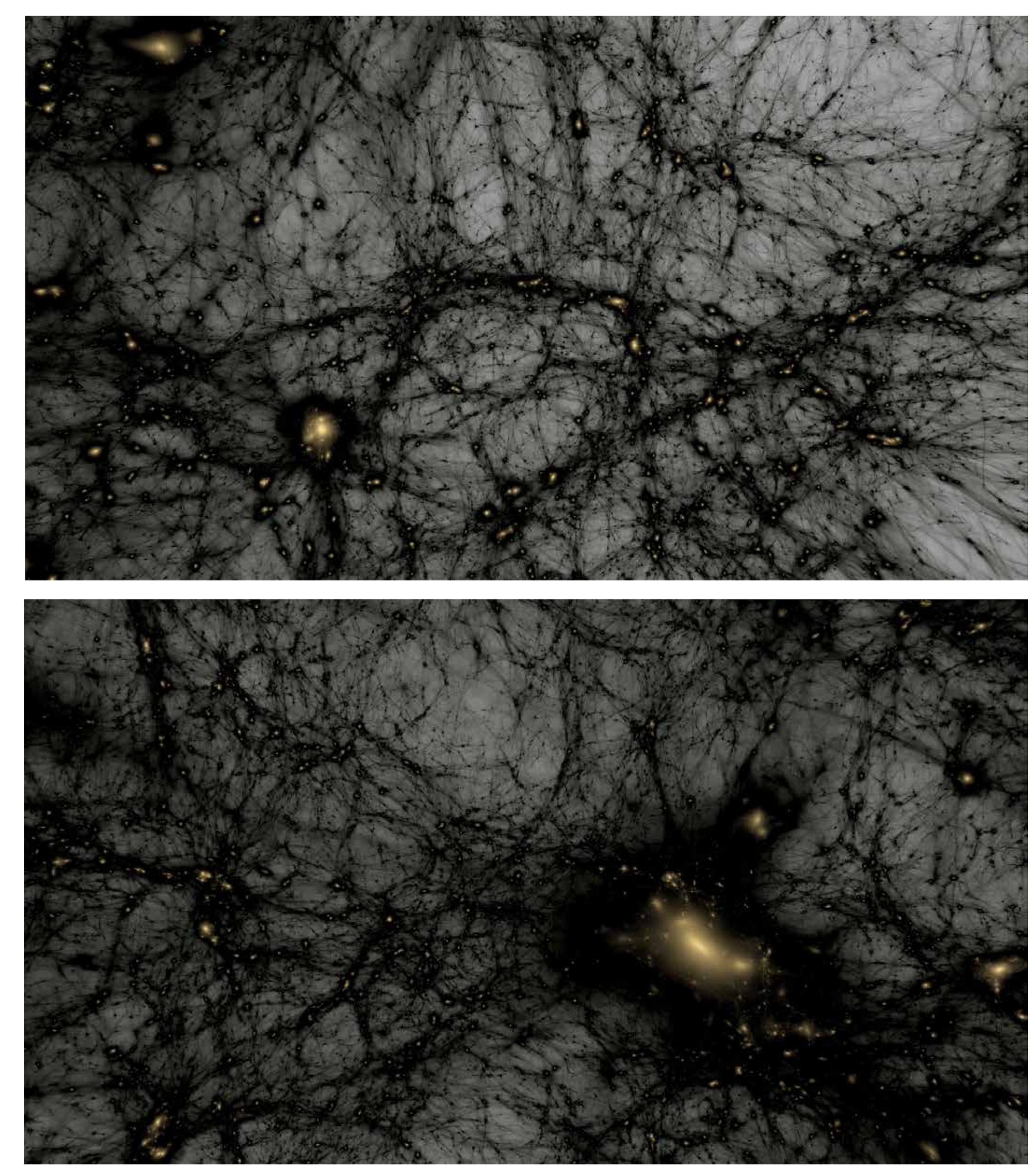


A density distribution from a dark matter simulation with about 134 million particles, resulting in about 804 million tetrahedra, respectively 3.2 billion triangles. The close-up on the left was rendered via the centroid approach (0.1 fps), whereas the image on the right was generated with the cell-projection approach (0.03 fps). For the image in the middle a hybrid approach was used, rendering the tetrahedral elements inside the sphere around the camera using the cell-projection methods and elements outside a sphere with the centroid methods (0.08 fps).

Application



The new visualization method was used to render a full-dome animation for the new space show "Dark Universe", produced and shown at the Hayden Planetarium (American Museum of Natural History) in New York City. Over 2000 time steps, each containing more than 3 billion tetrahedral elements, were rendered at about 24 million pixel resolution. (Image courtesy of D. Finnin, American Museum of Natural History)



Two snapshots of the simulation used for the Planetarium Show "Dark Universe" at the American Museum of Natural History. The sequence follows the formation of the cosmic web in a region about 500 million lightyears across. Over billions of years, gravity amplifies small density fluctuations and shapes filaments of dark matter, shown in black. The intersections of these filaments host massive clusters of galaxies, rendered in yellow.

References

[1] R. Kaehler, T. Abel, O. Hahn: "A Novel Approach to Visualizing Dark Matter Simulations", IEEE Transactions on Visualization and Computer Graphics (IEEE Scientific Visualization 2012), vol. 18, no. 12, December 2012.
[2] T. Abel, O. Hahn, R. Kaehler: "Tracing the Dark Matter Sheet in Phase-Space", Monthly Notices of the Royal Astronomical Society 2012.
[3] O. Hahn, T. Abel, R. Kaehler: "A New Approach to Simulating Collisionless Dark Matter Fluids", MNRAS, November 2012