7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Vlasov simulation in 6-dimensional phase space for cosmological neutrinos and its application to astrophysical magnetized plasma

Kohji Yoshikawa[1]
[1] Center for Computational Sciences, University of Tsukuba
e-mail (speaker): kohji@ccs.tsukuba.ac.jp

Kinetic simulation is a versatile method for simulating collective behavior of a huge number of particles under a certain Hamiltonian such as self-gravitating systems and magnetized plasma in astrophysical context. So far, these kinetic simulations have been performed with particle-based methods such as gravitational N-body simulations of dark matter in galaxies and galaxy clusters, and particle-in-cell (PIC) simulations of astrophysical magnetized plasma, in which matter distribution in a six-dimensional phase space is sampled in a Monte-Carlo manner by a finite number of discrete super-particles and their dynamics is numerically solved by integrating the equation of motion of each super-particle.

Although the particle-based numerical methods have been successful and primary options both in self-gravitating and magnetized plasma systems, there exist several intrinsic drawbacks in particle-based methods originating from the statistical sampling of matter distribution by super-particles. Such statistical sampling of matter distribution in the phase space introduces the well-known shot noise and critically compromises the numerical results, especially, for example, in simulating "hot" component with a large velocity dispersion, where the sampling of matter distribution is relatively sparse. Furthermore, matter in the high velocity tail, which is not well sampled in the particle-based methods, plays important roles in several important kinetic processes such as collisionless damping in the self-gravitating systems.

As a remedy for these shot noise in the particle-based methods, we, for the first time, implement a completely new approach (dubbed as Vlasov simulation/approach hereafter) that simulate the dynamics of matter by solving collisionless Boltzmann (Vlasov) equation based on a finite volume method.[1] This approach is free from the numerical problems described above by representing the matter distribution as a continuum medium in the six-dimensional phase space and enables us to perform completely noiseless simulations even when the velocity distribution has a broad and extended tail. Of course, this approach does not suit to all situations and the particle-based methods can be a better option for relatively "cold" matter with small extent of matter distribution in the velocity space. Therefore, a hybrid of N-body and Vlasov approaches is a desirable option which takes best advantage of both the particle-based and Vlasov approaches in a complementary manner.

Here, we present a Vlasov simulation of cosmological neutrinos which is combined with the particle-based N-body simulation of dark matter in the large-scale structure in the universe, as an example of such hybrid simulation of N-body and Vlasov simulations.[2] This hybrid approach to simulate the cosmological neutrinos exhibits clear advantages over the conventional particle-based N-body counterparts in terms of the shot noise seen in the particle-based simulations and the effective spatial resolution (see Figure 1).

Vlasov approach is also beneficial to simulation of magnetized plasma not only because it is not affected by the numerical shot noise but also because it is free from the constraints of the PIC method on the spatial resolution which must be chosen to be less than the Debye length, enabling us to perform a consistent simulation up to the MHD scale.

This research is supported by the Grant-in-Aid for Scientific Research byt the JSPS KAKENHI grant No. JP21H01079.

References

[1] K. Yoshikawa et al. ApJ, **762**, 116 (2013)
[2] K. Yoshikawa et al. ApJ, **904**, 159 (2020)

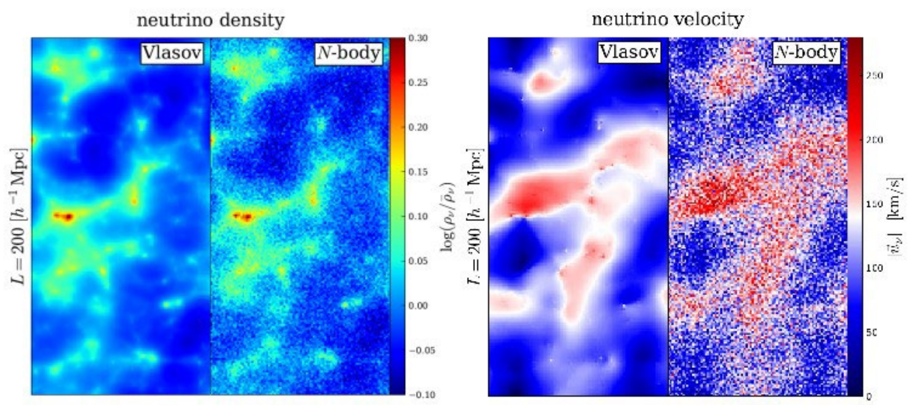

Figure 1. Density and velocity maps of neutrinos simulated with Vlasov and N-body simulations.