The Bondi universe: Can negative mass drive the cosmological expansion?

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SUPPLEMENTAL MATERIAL

I. UNSTABLE EVOLUTION FOR A PERIODIC SYSTEM

In Sec. IV of the main text, based on a linear response analysis of the mean-field Vlasov-Poisson equations, it was shown that an admixture of positive and negative masses is always unstable, except in the special case where the two equilibrium distributions $f_{eq\pm}(v)$ are identical. The instability rate is proportional to the square root of the wave number, $\mathrm{Im}(\omega) \sim \sqrt{k}$, hence shorter wavelengths grow more rapidly.

Here, we show results of N-body numerical simulations that confirm such instability. We use periodic boundary conditions with period $L = N = 4 \times 10^3$ and Maxwellian equilibria for both positive and negative mass species, with thermal velocities $v_{T\pm}$. We study three cases, for which the thermal velocities satisfy, respectively: $v_{T-} \ll v_{T+}$ (Fig. 1), $v_{T-} \gg v_{T+}$ (Fig. 2), and $v_{T-} = v_{T+}$ (Fig. 3).

For the two cases of unequal thermal velocities (Figs. 1 and 2), the linear response theory predicts instability. As expected, short wavelengths quickly begin to grow during the linear phase ($t = 0 - 3$). Later, nonlinearities lead to the formation of complex phase-space structures ($t = 10 - 30$). For even longer times ($t \approx 100$), these structures become elongated and form filaments.

The case $v_{T-} = v_{T+}$ (Fig. 3) should be stable according to the collisionless (mean field) linear response theory. However, the simulations were performed with the exact N-body code, which incorporates both collisionless and collisional effects. As the number of particles is finite, the two equilibrium Maxwellians are not exactly identical. Hence, the instability still occurs, although it is slower compared to the other cases. Indeed, in the equal thermal speed case of Fig. 3, fully nonlinear structures develop only around $t = 32$, while they are visible as early as $t = 10$ in the cases with different thermal speeds (Figs. 1 and 2).

II. FORMATION OF BONDI PAIRS

In a short movie (see below), we show the phase-space dynamics for a relatively small ($L = N = 500$) and cold ($\sigma_V(0) = 100$) system, which makes it easier to follow individual particles. Positive mass particles are depicted as red crosses and negative mass particles as blue squares.

The formation of stable Bondi pairs is evidenced by the fact that only the blue squares are visible, the red crosses being hidden behind them. The Bondi pairs become dominant around $t = 2 \times 10^4$, when two streams of pairs are clearly visible. After that time, each pair travels together as a single unit. The two streams have opposite polarity (i.e., $+/-$ or $-/+$), and therefore accelerate either to the left or to the right. Occasionally, the particles in one pair switch positions, changing polarity, and start accelerating in the opposite direction, hence joining the other stream. The simulation stops when no more particle crossings are observed. From that time on, the system evolves as a gas of independent Bondi pairs, each moving with constant acceleration in either direction.

Watch the movie in the Supplemental Material.

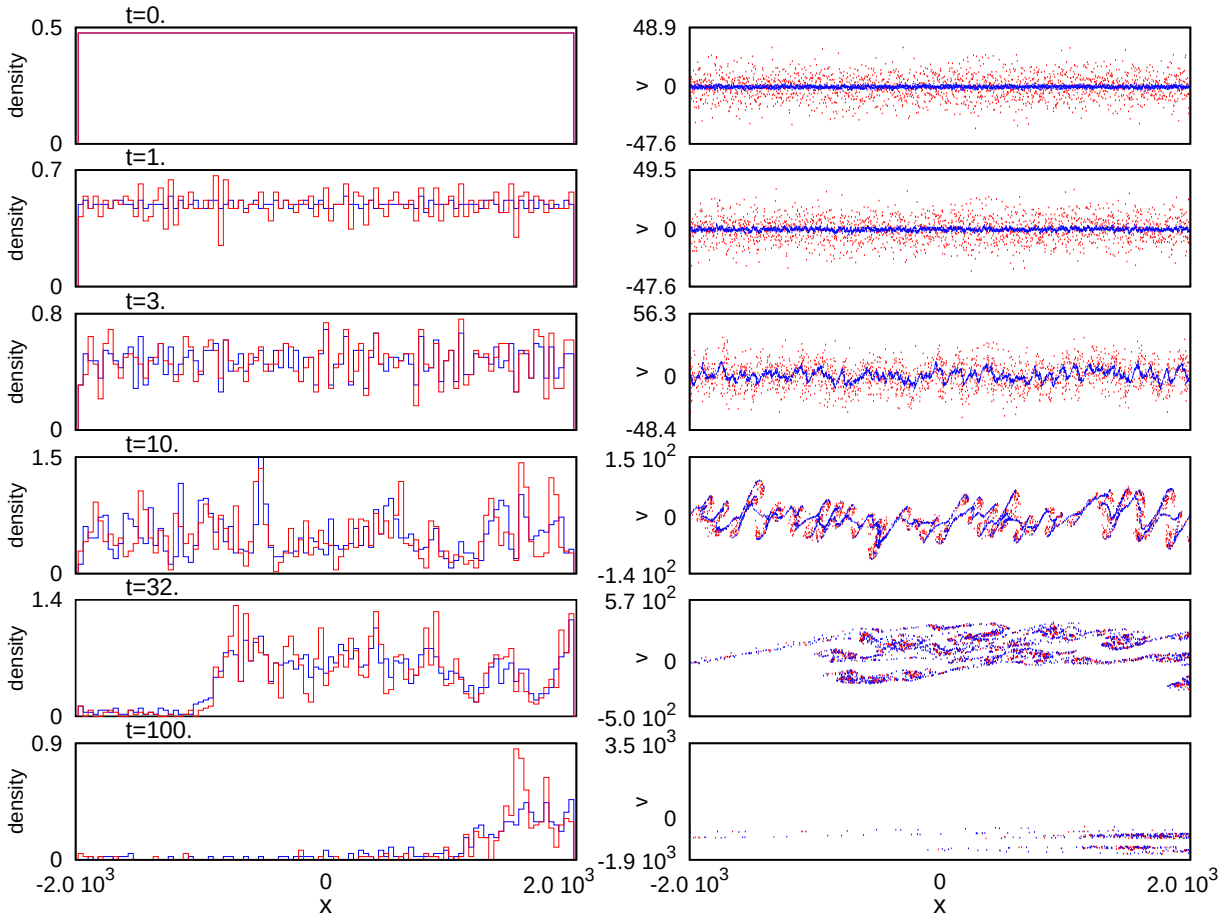


FIG. 1. Periodic boundary conditions. Density plots (left panels) and phase space portraits (right panels) for positive mass particles (red) and negative mass particles (blue). The thermal velocities are $v_{T-} = 1$ and $v_{T+} = 10$. The length of the domain is $L = N = 4 \times 10^3$.

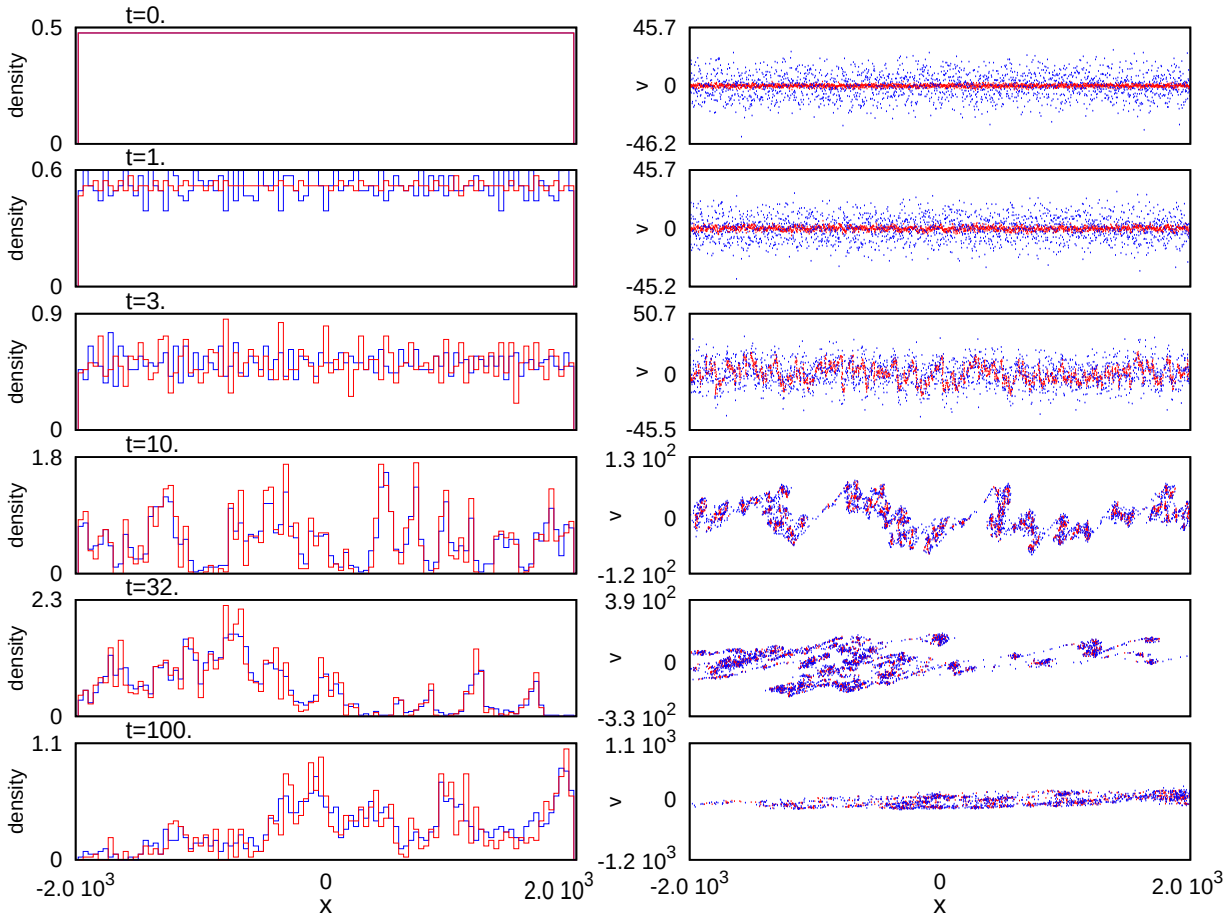


FIG. 2. Periodic boundary conditions. Density plots (left panels) and phase space portraits (right panels) for positive mass particles (red) and negative mass particles (blue). The thermal velocities are $v_{T-} = 10$ and $v_{T+} = 1$. The length of the domain is $L = N = 4 \times 10^3$.

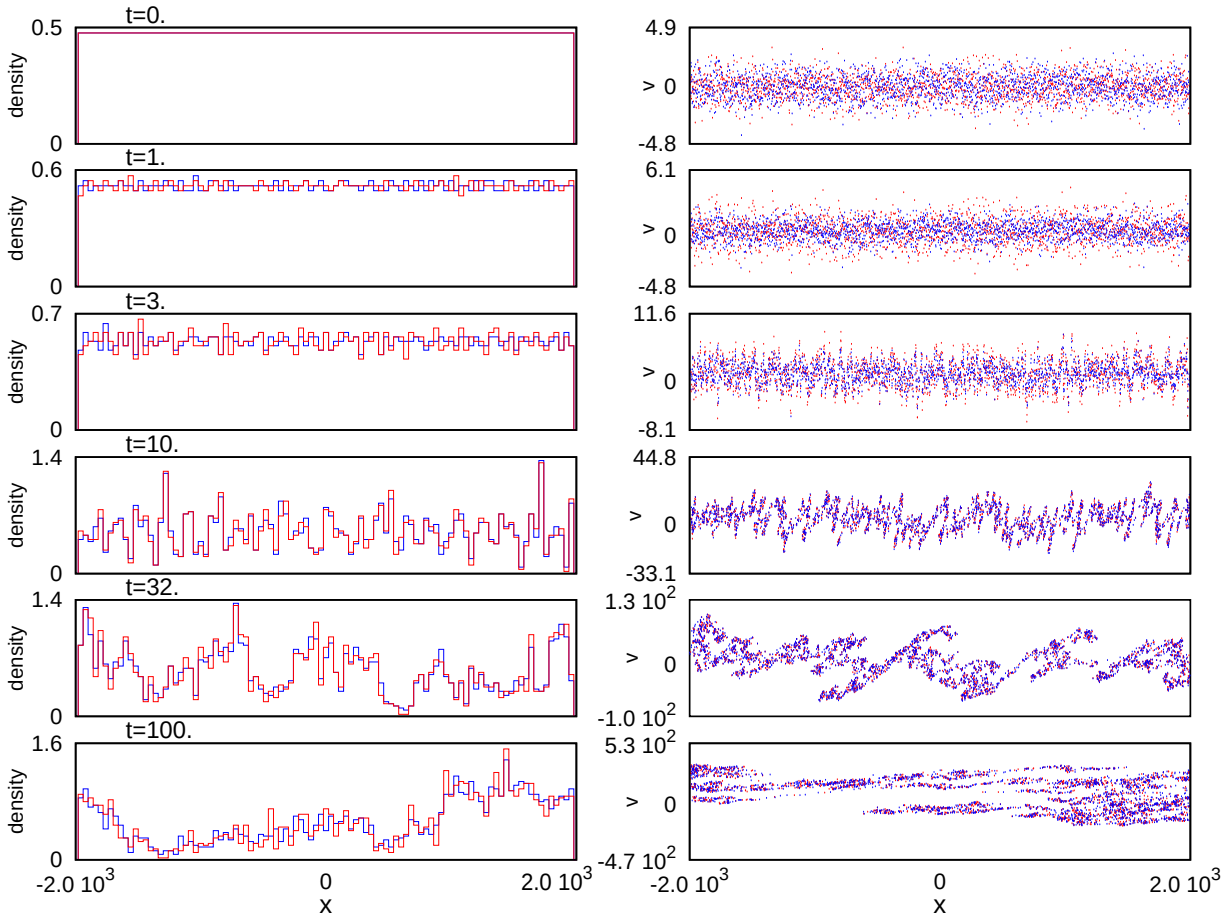


FIG. 3. Periodic boundary conditions. Density plots (left panels) and phase space portraits (right panels) for positive mass particles (red) and negative mass particles (blue). The thermal velocities are $v_{T-} = v_{T+} = 1$. The length of the domain is $L = N = 4 \times 10^3$.