Simulation of Gravitational Superclustering of Massive Neutrinos

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Results of a numerical simulation of large-scale, plane, symmetric gravitational clustering of massive neutrinos are presented. It is shown that neutrinos may cluster in galactic halos in the adiabatic scenario of galaxy formation. The population of test particles exhibits very little phase mixing, suggesting that the scale of galactic halos may be set by the neutrino mass.

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Massive neutrinos may dominate the universe's rest mass[1,2] and provide the "missing mass" indicated by dynamics on scales from galactic halos through superclusters. The "gravitational Landau damping" process wipes out density perturbations on a controversial scale of order tens of megaparsecs.[3-7] The average velocity of collapse of such structures is of order 1000 km s^{-1}. The disparity between these sizes and velocity dispersions with those of galactic halos had led to the conclusion that they cannot form from collapse of such structures.[5,6,8-10]

It has been suggested that the universe exhibits a cell structure with large voids,[11-17] and that spiral galaxies preferentially inhabit the faces.[16] A numerical simulation[18] of a universe with a lower cutoff in perturbation wavelength has led to a cell structure, partly due to the accelerating ellipticity of collapsing objects.[19] This work is an extension of that simulation, using a one-dimensional slab, symmetric, plane-wave scalar density enhancement as the initial condition. This was evolved using the cloud-in-cell[20-23] (CIC) method on a 1000-grid field, with periodic boundary conditions, fixed in comoving coordinates.

Ten thousand particles were uniformly placed but for a perturbation in the spacing, and with zero velocity with respect to the Hubble flow. The same number of test particles were distributed with the same spacing, but a velocity assigned under the "quasithermal" distribution function of a homogeneous massive neutrino background.[8] The test particles were not to contribute to the gravitational field, so as to prevent unphysical rms density fluctuations: The random motions of our small number of particles would create large-amplitude "noise" which would not happen in real large-N neutrino perturbations. This results in not including the neutrino thermal pressure. The effect is small since the Jeans length is already much smaller than our wavelength; the approximation improves as infall velocities exceed quasithermal velocities.

The wavelength of the perturbation was 100 Mpc (megaparsecs). Infall velocities and linear dimensions are proportional to the scale factor set by this wavelength. The results shown are for $m = 30$ eV, $g = 4$, and H (the Hubble constant) $= 75$ km s^{-1} Mpc^{-1}. This then simulates a closed universe, $\Omega \sim 1.07$. Other test cases were run with no qualitatively different results. The cosmological constant and neutrino chemical potential were set to zero.

Energy conservation was checked against the "cosmic energy theorem."[24,25] No more than 1% deviation was found, a considerable improvement over other calculations of this kind.[18]

The collapse began with a sinusoidal perturbation $\delta\rho/\rho \sim 10^{-3}$ at $z = 10^4$. The collapse went nonlinear ($\delta\rho/\rho \sim 1$) near $z \sim 10$, and a strong density enhancement took place near $z = 5$, when test particles were trapped in the central region.

A snapshot of the phase space as of $z = 0$ may be seen in Fig. 1. The solid line connects the positions of the massive particles in phase space, and a cross is drawn at the position of every 100th test particle. At each point near the center, there are coexisting streams of particles. There is considerable concentration of particles into the central lump, shown in increased resolution in Fig. 2, where *all* test particles in this region are plotted. This section of phase space did not change substantially (except for rotation and windup) since $z = 5$. It has linear dimensions and velocity dispersion similar to a galactic halo. The velocity dispersion of *all* particles (of either type) is ~ 1200 km s^{-1}, but it is much lower in this region. Thus the arguments about velocity dispersion are invalidated; the emergence of the needed neutrino population is found to be a natural outcome.

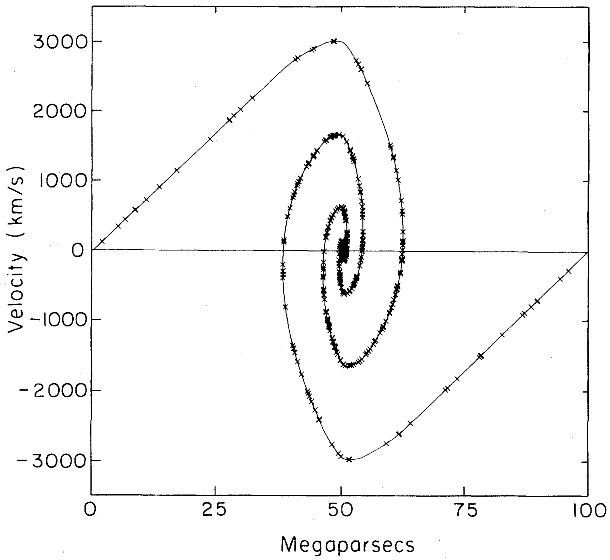

FIG. 1. Phase space of collapsed perturbation.

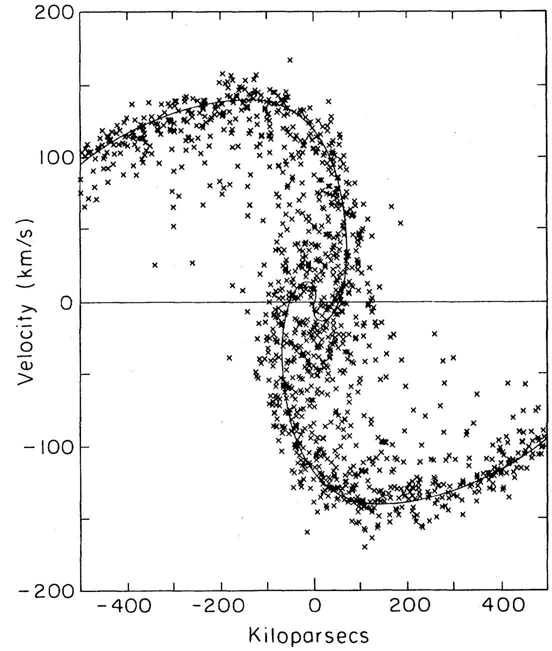

FIG. 2. High-resolution view of central region of phase space.

Phase mixing has also been considered as an argument (unpublished) against the formation of galactic halos in the adiabatic scenario (collapse of large-scale flattened structures). If neutrinos are both to fit the phase space of galactic halos and to provide not too much mass density to the universe, their phase-space density in galactic halos must be very high, close to the maximum of the primordial quasithermal distribution.[8] If one averages the phase-space density of test particles over all the spiral-enclosed region in Fig. 1, it of course is much reduced from its initial value. Yet not too much phase mixing can be allowed, or the neutrino mass required would be so large as to violate constraints on the mass density of the universe.

The phase-space density of the condensed region was measured, and divided by its initial maximum value, and found to be $93 \pm 2\%$ in all cases. This central region comprised about 12% of the total mass.

Therefore the formation of semidegenerate condensations is to be expected in this sort of collapse. (I use semidegenerate to describe the "half-full" phase space.) I suggest that the Tremaine-Gunn phase-space constraint[8] may in fact be an equality, rather than an inequality, for galactic halos, suggesting a neutrino mass around 30 eV. It is possible that the mass within the disk radius is dominated by massive neutrinos.[26] Examination of galactic rotation curves[27] suggests that larger asymptotic rotation velocities are reached at a smaller radius. If galaxies are dominated by semidegenerate neutrino halos, this anticorrelation is expected from the phase-space constraint. (It should be emphasized that this constraint is a necessary, but not sufficient, condition for collapse on various scales.)

A plot of total mass density across the field (not shown here) shows strong spikes, which are regions of density enhancement a few megaparsecs from the central plane. These are very persistent, not moving much with respect to the Hubble flow since $z = 3$. They are located near the turnaround point of the velocity streams. It has been suggested[28,29] that the local supercluster exhibits minima parallel to the plane, with maxima in galaxy density a few megaparsecs from it, in parallel arrays. I speculate that galaxies could preferentially form near these regions of lesser density enhancement.

In summary, I have shown that, in the case of slab symmetry, the collapse of large-scale perturbations of collisionless particles can lead to condensations on a much smaller scale; these condensations have a much lower velocity dispersion than the phase space as a whole; and these condensations exhibit little phase mixing, so that a population of neutrinos which may cluster in galactic halos arises naturally in the adiabatic scenario with massive neutrinos.

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