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Experimental Cosmology: The Early Universe After COBE

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Our simulations of the Cold Dark Matter model (CDM) on parallel supercomputers have shown that the galaxy-galaxy velocity dispersion at small scales is consistent with results obtained from the CfA sky survey. This is significant, since velocity dispersion limits had been previously used to rule out the model. Similarly, we have shown that the redshift-space power spectrum (also used to rule out CDM) does not provide an unambiguous constraint at small scales, and is consistent with the power spectrum measured in the IRAS galaxy catalog. The comparison between the numerical experiments and the observations is not as straightforward as was usually assumed, both because of a significant scatter of velocity dispersions between different observation-sized samples, and because of the importance of clusters.

1. Background and Research Objectives

A full understanding of galaxy evolution can not be obtained with purely analytic techniques. The best tool available to investigate the consequences of particular cosmological theories is the parallel supercomputer. Recent advances in both hardware and software allow accurate numerical simulations of complex, nonlinear astrophysical phenomena to be carried out. Our simulations of large scale structure over the past several years have allowed us to perform controlled numerical experiments, evolving the universe from the Big Bang to the present. These N-body simulations represent the state-of-the-art in numerical cosmology and parallel N-body algorithms, consuming over 5 petaflops (5 times 10 to the 15th power floating point operations) to date.

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Without such computer experiments the study of cosmological structure formation would be virtually impossible. Galaxy formation is characterized by multiple spatial and temporal scales which must be accounted for in an effort to gain insight into the nature of the astrophysical processes which shape galaxies. In our project to tackle these problems, we have developed a software infrastructure based on parallel tree data structures which is capable of solving a large class of problems efficiently on parallel supercomputers.

Gravitational interaction directly couples perturbations on various scales in the nonlinear regime. Therefore, accurate computer experiments with a broad dynamical range are indispensable. Furthermore, the final appearance of the Universe will reflect the underlying distribution of matter only in a very indirect way. This is because most ($> 90\%$) of the mass content of the Universe is "dark," interacts only gravitationally, and does not emit any radiation. The visible galaxies form only in the selected high density ($> 10^3$ denser than average) collapsed density peaks known as "halos."

The paramount importance of numerical simulations in explaining the origin of structure on cosmological scales was recognized very early: Numerical experiments eliminated the light neutrino as a candidate for dark matter — the resulting "hot dark matter" (HDM) Universe produced collapsed objects which were simply too massive to be identified with the observed clusters of galaxies, or, for that matter, with anything else. The task of assessing viability of CDM proved much more difficult. The reason was that HDM had nearly no density fluctuations on small scales. Thus, the structure developed starting on large scales ("top-down"), and small scale resolution was not needed to arrive at the verdict. By contrast, CDM has a lot of power on small scales, and the structure develops hierarchically, "bottom up," with the smallest, sub-galactic clumps forming first, and with the appearance of larger scales "inherited" to a large degree from the "previous generations."

Nevertheless, in the wake of success with HDM simulations, numerical experiments were carried out in the CDM models using N-body codes with $N \sim 10^4$ (Davis et al., 1985). This number of particles was only a factor of a few larger than the expected numbers of galaxies, so the (very uncertain) identification of which of the N-body particles should be regarded as galaxies became a crucial step, and the hierarchical aspects of structure development were essentially ignored. The results were that if the galaxies were distributed similarly to matter, i.e. $(\delta \mathcal{N}/\mathcal{N})_{GALAXIES} = (\delta M/M)_{MASS}$, then their relative velocities would be a factor of ~ 5 larger than observed. While the observations were (and still are) somewhat uncertain, such a glaring discrepancy called for a modification of the CDM model. The way out was to suggest a *biased* version of CDM, with galaxies exaggerating the distribution of mass by a bias factor b; $(\delta M/M)_{GALAXIES} = b(\delta M/M)_{MASS}$, $b \sim 2.5$. Such biasing would allow one to decrease the underlying mass variations, which are ultimately responsible for velocities of galaxies, and, thus, help reconcile CDM-predicted $\delta M/M$ with the observations. This idea is no longer viable: COBE has set $b = 1$ with a accuracy of about 20%. However, in the meantime, conclusions of these early simulations were called into question by somewhat improved, more recent simulations with $\sim 10^6$ particles, where a galaxy contained a few particles (Couchman and Carlberg 1992). Unfortunately, while their resolution was significantly better than in the previous runs, interpretation of their results still required an uncomfortably large element of guesswork. Moreover, it has become rather clear that this is the "end of the line" for serial computers.

2. Importance to LANL's Science and Technology Base and National R&D Needs

Tree-based codes can solve a very general class of problems that can be expected to grow in importance as the need for spatial adaptivity becomes necessary for the simulation of ever more difficult problems. Problems of current interest in a wide variety of areas rely heavily on methods very similar to those we are using. We are directly familiar with applications in computational biology (protein folding, thermodynamics in aqueous solution), electromagnetic scattering, fluid mechanics (vortex method, panel method), molecular dynamics, materials science (dislocation dynamics, boundary element methods) and plasma physics, but there are certainly more.

Essential to the transition to parallel computing is the existence of adaptable codes which will parallelize a variety of applications so that users only need to specify the "physics" of a problem and not the details of data structures, load balancing, interprocessor communication, etc. Our work has demonstrated real progress toward that goal.

Two situations arise again and again in a variety of particle algorithms: (1.) finding neighbor lists for short-range interactions, and (2.) computing global sums for long-range interactions. For example, the problem of finding neighbors within the cutoff radius of a Lennard-Jones potential in a molecular dynamics simulation is qualitatively the same as finding neighbors in an SPH simulation. Similarly, the Biot-Savart summations that appear in vortex dynamics simulations are essentially the same as the Newtonian interactions that occur in astrophysics. One simply has a "vector mass" to contend with that adds somewhat to the complexity, but little to the essential underlying algorithm. Treecodes offer efficient and parallel solutions to both these situations which transcend the individual problem domains.

Software that is portable between different disciplines is an elusive but highly desirable commodity. It is virtually guaranteed that a project focused exclusively on a particular problem will not produce software that can easily be used outside that discipline. Appropriate abstractions do not emerge without careful analysis and design. We have specifically designed the software described here so that it can be used in a variety of areas. We use a single implementation of the underlying data structures to support all of these "applications." These tasks are diverse enough to require a careful design of interfaces and libraries in such a way that the "physics" is cleanly separated from the "data structures." We believe that the effort of designing a clean, highly modular implementation has not only saved us time (since we have been re-using our own software in separate sub-problems) but is also allowing us to leverage our work to speed the development of high-quality parallel software in a variety of unrelated fields. It is software such as this which is critical to the continuing development of strategic computing in support of science-based stockpile stewardship.

3. Scientific Approach and Accomplishments

We have used a treecode algorithm somewhat similar to that originally introduced by Barnes and Hut (1986) which runs on highly parallel supercomputers. The runs were carried out on the 512 processor Intel Touchstone Delta and Intel Paragon systems at Caltech. A combination of treecode software and a massively parallel computer allows us to use enough particles ($N \sim 17.2 \times 10^6$ or 8.8×10^6) to be able to directly identify halos as collapsed objects at $z = 0$, in a computational volume large enough to accurately model the CDM spectrum. In addition, we use a relatively small softening parameter of 20 kpc, which gives us roughly four orders of magnitude in dynamical range. This is sufficient to accurately model the collapse, dynamics and mergers of the dark matter halos which have formed in abundance in our simulations. More than 10^4 halos (with central density no less than 10^4 above background, and typically tens to hundreds of particles each) form per run by the "present" $z = 0$.

Halos are found to be less correlated than mass on megaparsec scales, in agreement with the results of Couchman and Carlberg (1992). This "anti-bias" is the result of the variation of the average halo mass with the density of the local environment: halos in denser regions are systematically more massive, and are likely to be associated with more light.

The volume density of halos as a function of their mass inside a 100 kpc radius has been determined for our simulations. When the halo mass is converted to luminosity by a mass to light ratio f of the stellar population and a dark to bright mass ratio D/B, then the resulting "luminosity" function is rather similar in shape and amplitude to the Schechter function usually employed to fit observations. Thus we do not significantly overproduce sub-structureless, massive halos in our high resolution simulations in contrast to the findings of White et al. (1987) and Gelb et al. (1993). This conclusion is confirmed by the distribution of circular orbit velocities of our halos in our undernormalized $\sigma_8 < 1$ simulations: Out of $\sim 10^4$ halos per simulation only a few ($\sim 0.2\%$) have maximal v_{circ} above 550 km/s within 100 kpc, with the highest value being ~ 700 km/s.

We initiated our simulations motivated by the desire to eliminate what we have perceived as the only "weak link" in using σ_v as an argument against CDM — the identification of galactic halos with individual particles in nearly all previous numerical experiments. The discrepancy reported in the above paragraph appears to confirm the prevailing prejudice against COBE – normalized cold dark matter. Nevertheless, we have now — after careful analysis of our simulations and a re-analysis of the observations — come to the conclusion that σ_v is (i) a poor statistic, and (ii) it is estimated from the observational data in a manner which differs from the way σ_v is computed from numerical experiments. Indeed, when the methods used to analyze the observations are applied to the halo catalogs obtained from the numerical experiments, (i) estimates of σ_v vary significantly between distinct observation-sized halo samples, and (ii) values of ~ 450 km/s are obtained for a significant number of samples extracted from the somewhat undernormalized ($\sigma_8 \simeq 0.7$) models at Mpc separations.

To some degree, the discrepancy between the observed and the usually quoted numerical estimates of σ_v is decreased by the velocity bias in our simulations. It is nearly a factor of two on 100 kpc scales, becoming somewhat smaller ($b_v \sim 0.7$) on megaparsec scales. This bias (first noted by Carlberg (1991)) is too large to be attributed solely to the differences between the motions of centers of mass of the collapsed objects and particles inside them. However, it is also too small to erase the difference between the usually quoted observational estimate of σ_v and the average halo motions obtained from our numerical experiments.

In contrast to numerical experiments, which allow one to compute σ_v directly from the three-dimensional data on velocities and positions, observations provide one only with the angular separations and redshifts of galaxies. The method of Davis and Peebles (1983) is based on the comparison of the correlation functions in redshift with the correlation functions in the direction transverse to the line of sight. In the absence of peculiar motions, redshifts would translate directly to the line-of-sight distances and the two correlation functions would be identical. However, dispersion caused by peculiar velocities increases the spread in the redshift distribution. This increase in spread can be translated into a typical pairwise dispersion σ_v with the help of a few plausible assumptions, such as the form of the velocity distribution.

In applying this procedure to the CfA survey Davis and Peebles have corrected the data for Virgocentric infall. This correction seems to be crucial, as it lowers the estimated σ_v from well above 500 km/s to below 400 km/s. The exact value of the estimated σ_v depends on one more correction, which accounts for the non-virgocentric, mean motion of galaxies toward each other caused by gravitational attraction, as well as on some other details of the analysis which do not seem to have too much impact on the estimates.

Having verified its validity in such "artificial" catalogs, we have also applied our Davis-Peebles-like algorithm to the observations. We shall report details of this analysis elsewhere. Let us note that when the sample is selected by directly interpreting redshift as a distance indicator for the computation of absolute magnitudes, σ_v for the CfA sample is 580 km/s. Selecting the sample in a more sophisticated manner, which attempts to correct for Virgocentric infall when computing distance from redshift, results in $\sigma_v = 540$. In order to get a result close to the usually quoted 340 km/s we must either exclude galaxies within 10 degrees of the core of Virgo or subtract Virgocentric infall from the peculiar velocities. Needless to say, neither of these steps is used in the analysis of numerical experiments.

It should be emphasized that, without the Virgocentric infall correction, typical values of $\sigma_v \sim 500$ km/s or more inferred from the northern sky CfA survey are in reasonable accord with the similarly "uncorrected" estimates obtained from our numerical experiments. In view of these results it would therefore appear that there is no statistically significant discrepancy between the observations and predictions of the CDM/COBE model for peculiar velocities.

We feel that our cautionary remarks concerning the reliability of σ_v should be kept in mind when analyzing other data sets (such as the IRAS survey). We have not yet had a chance to apply these methods of analysis to that sample. However, in view of the above discussion, the use of IRAS galaxies is bound to under-represent cluster cores, which have had a decisive impact on the value of σ_v inferred from the CfA Northern Sky survey. Thus, we expect that the derived σ_v will underestimate the true "ensemble average" (to the extent to which such a concept even makes sense in view of our conclusions above). Moreover, extrapolation of the small-scale σ_v to $\sim 10h^{-1}$ Mpc scales is likely to be affected by the asymmetry of the distribution of pairwise radial peculiar velocities we have detected on these scales.

While these simulations have answered several questions, there is still an almost embarassing richness of unexplored alternatives. Fortunately, all of the alternatives will soon confront even more precise observational data, and their success will be evaluated by means of larger and more accurate simulations.

Publications

1. T. G. Brainerd, B. C. Bromley, M. S. Warren, and W. H. Zurek, "Velocity dispersion and the redshift space power spectrum," *Ap. J. (Letters)*, (1996) (in press).
2. B. C. Bromley, T. G. Brainerd, R. Laflamme, and M. S. Warren, "Peculiar velocities in numerical simulations: An examination of redshift-space power," in *Heron Island Workshop on Peculiar Velocities*, P. J. Quinn, editor (1995).
3. B. C. Bromley, T. G. Brainerd, M. S. Warren, W. H. Zurek, and P. J. Quinn, "On cluster cores and power spectra," in *Clustering in the Universe*, Proceedings of the XXXth Moriond Meeting (1995).
4. B. C. Bromley, R. Laflamme, M. S. Warren, and W. H. Zurek, "Testing theories of structure formation," in *Clusters, Lensing & the Future of the Universe*, Proceedings of the 1995 Meeting of the Astronomical Society of the Pacific, V. Trimble and A. Reisenegger, editors (1995).
5. B. C. Bromley, M. S. Warren, W. H. Zurek, and P. J. Quinn, "Rich cluster simulation: Dynamics and mass estimates," in *Dark Matte*r, Proceedings of the Fifth Annual Astrophysics Conference in Maryland, S. Holt and D. Bennett, editors, 433-436, New York (1995).
6. B. C. Bromley, T. G. Brainerd, M. S. Warren, and W. H. Zurek, "Cosmic structure on small scales: Results on cluster cores and redshift-space power spectra," in *Mapping, Measuring and Modelling the Universe*, Valencia Proceedings, P. Coles, editor (1996).
7. B. C. Bromley, T. G. Brainerd, M. S. Warren, W. H. Zurek, and P. J. Quinn, "On cluster cores and redshift-space power spectra," in *Clustering in the Universe*, Moriond Proceedings, S. Maurogordato, editor (1996).
8. B. C. Bromley, R. Laflamme, M. S. Warren, and W. H. Zurek, "The distribution of matter around luminous galaxies, " in *Proceedings of the XXXIth Moriond Meeting* (1996).

9. B. C. Bromley, M. S. Warren, and W. H. Zurek, "Estimating omega from galaxy redshifts: Linear flow distortions and nonlinear clustering," *Ap. J. (Letters)* (1996).

10. J. K. Salmon, M. S. Warren, and G. S. Winckelmans, "Fast parallel treecodes for gravitational and fluid dynamical N-body problems," *Intl. J. Supercomputer Appl.*, **8**, 129–142 (1994).

11. M. S. Warren and J. K. Salmon, "A fast treecode for many-body problems," in *Los Alamos Science*, **22**, 88–97, N. G. Cooper, editor, Los Alamos National Laboratory, Los Alamos, NM (1994).

12. M. S. Warren and J. K. Salmon, "A parallel, portable and versatile treecode," in *Seventh SIAM Conference on Parallel Processing for Scientific Computing*, 319–324, Philadelphia (1995).

13. M. S. Warren and J. K. Salmon, "A portable parallel particle program," *Computer Physics Communications*, **87**, 266–290 (1995).

14. M. S. Warren and J. K. Salmon, "Abstractions and techniques for parallel N-body simulation," in *Parallel Object Oriented Methods and Applications (POOMA) '96* (1996).

15. M. S. Warren, W. H. Zurek, B. C. Bromley, T. G. Brainerd, J. K. Salmon, and P. J. Quinn, "N-body simulation of the cold dark matter cosmology," in *Images of Earth and Space: The Role of Visualization in NASA Science*, J. Cohen, editor (1995).

16. M. S. Warren, "Experimental Cosmology Using Fast Parallel N-body Methods," PhD thesis, University of California, Santa Barbara (1994).

17. W. H. Zurek and M. S. Warren, "Experimental cosmology and the puzzle of large-scale structure," in Los Alamos Science, **22**, 58–81, N. G. Cooper, editor, Los Alamos National Laboratory, Los Alamos, NM (1994).

18. W. H. Zurek, P. J. Quinn, J. K. Salmon, and M. S. Warren, "Large scale structure after COBE: Peculiar velocities and correlations of cold dark matter halos," *Ap. J.*, **431**, 559–568 (1994).

19. W. H. Zurek, B. C. Bromley, and M. S. Warren, "Second coming of cold dark matter?" in *Dark Matter*, Proceedings of the Fifth Annual Astrophysics Conference in Maryland, 397–406, S. Holt and D. Bennett, editors, New York (1995).

References

Barnes, J. and P. Hut, "A Hierarchical O($N\ logN$) Force-Calculation Algorithm," *Nature*, **324**, 446 (1986).

Carlberg, R. G., "Dynamical Biases in Gravitational Clustering," *Ap. J.*, **367**, 385–392 (1991).

Couchman, H. M. P. and R. G. Carlberg, *Ap. J.*, **389**, 453 (1992).

Davis, M. and P. J. E. Peebles, *Ap. J.*, **267**, 465 (1983).

Gelb, J. M., B. Gradwohl, and J. A. Frieman, *Ap. J. (Letters)*, **403**, 5 (1993).

White, S. D. M., M. Davis, G. Efstathiou, and C. S. Frenk, *Nature*, **330**, 451 (1987).

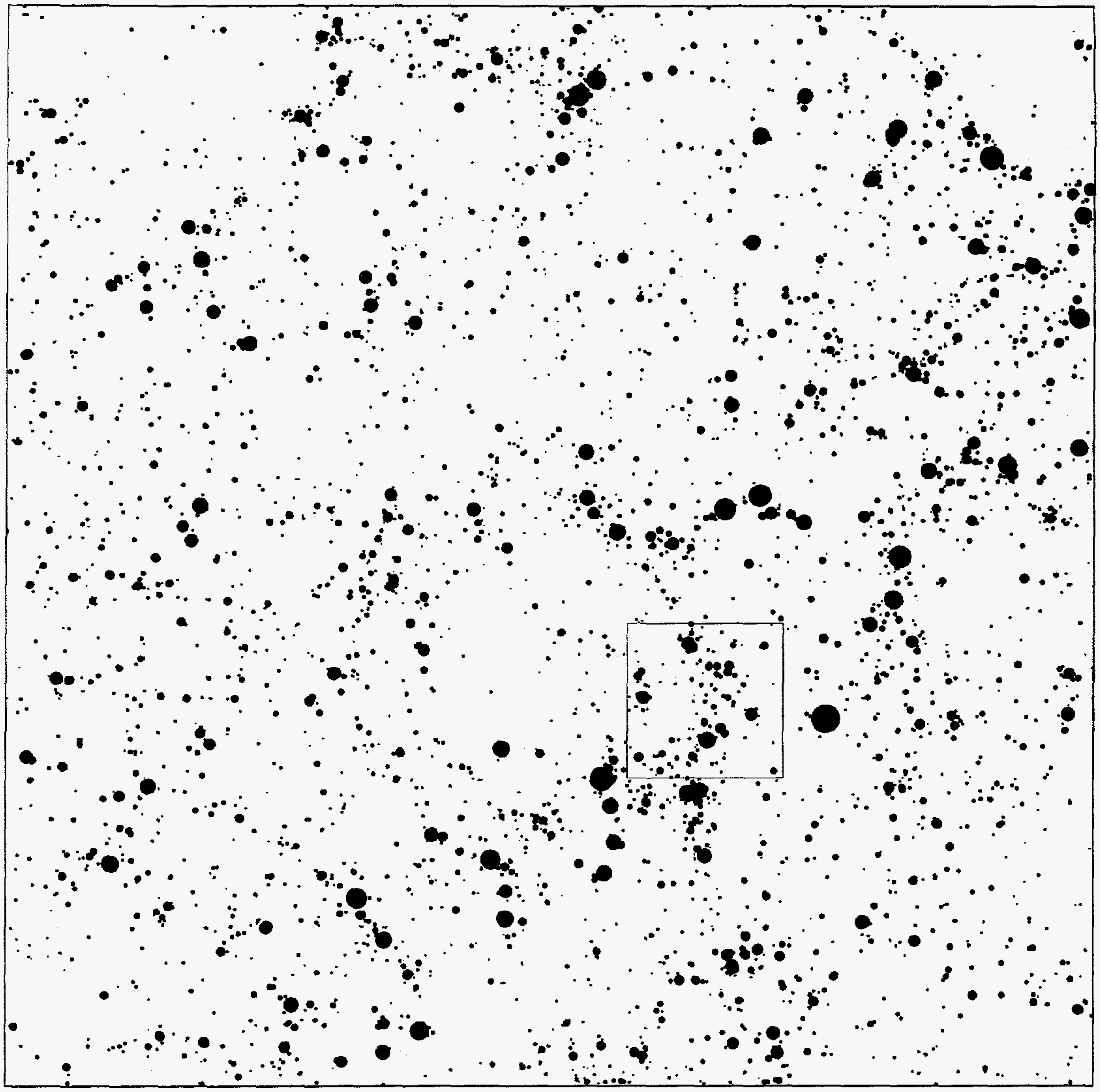

Figure 1: A plot of the projected locations of “galactic halos” in one of the N-body models. The size of the square is about 180 Mpc across. Sizes of the dots are approximately proportional to the masses of the halos. The small square indicates the region which is shown in more detail in the next figure.

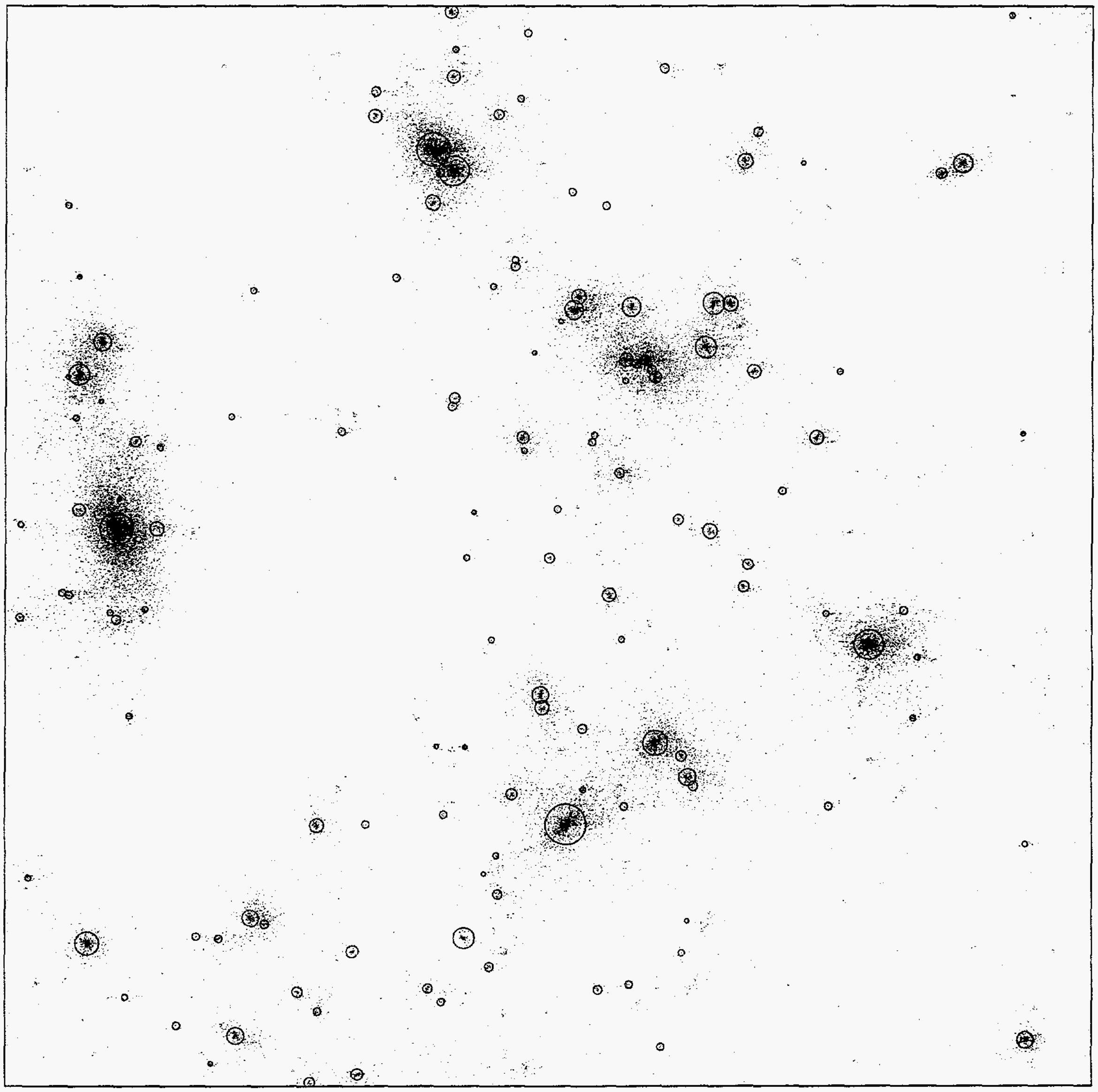

Figure 2: A high-resolution plot of every particle (about 250,000 of them) in one 50th of the total system (indicated by the small square in the previous figure), with the circles representing the location of galaxy halos.

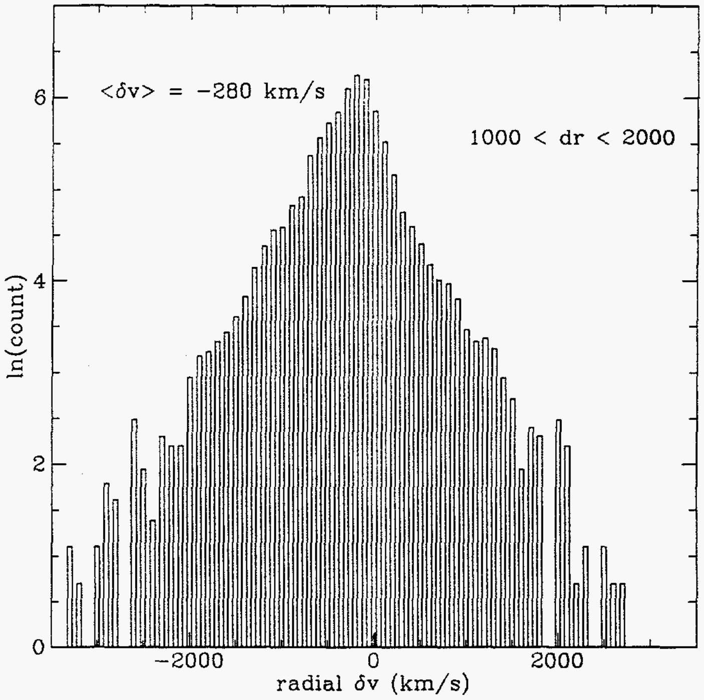

Figure 3: Distribution of the number of pairs as a function of pairwise radial velocity. The triangular shape of this histogram over a large range of δ_v implies that the distribution is indeed exponential, and the fact that the diagram appears isosceles allows us to infer the velocity dispersion σ_v from the slope.