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### High performance N-body simulation on computational grids

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## Bibliography

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- [1] S. J. Aarseth. Dynamical evolution of clusters of galaxies, I. *MNRAS*, 126:223–255, 1963.
- [2] S. J. Aarseth. Direct n-body calculations. In J. Goodman and P. Hut, editors, *Dynamics of Star Clusters*, volume 113 of *IAU Symposium*, pages 251–258, 1985.
- [3] S. J. Aarseth. From NBODY1 to NBODY6: The Growth of an Industry. *Publications of the Astronomical Society of the Pacific*, 111:1333–1346, November 1999.
- [4] S. J. Aarseth. *Gravitational N-Body Simulations*. Cambridge University Press, Cambridge, UK, November 2003.
- [5] D. Abramson, J. Giddy, and L. Kotler. High performance parametric modeling with nimrod/g: Killer application for the global grid? In *Proceedings of the 14th International Parallel and Distributed Processing Symposium '00*, page 520, Los Alamitos, CA, USA, 2000. IEEE Computer Society.
- [6] G. Allen, D. Angulo, I. Foster, G. Lanfermann, C. Liu, T. Radke, E. Seidel, and J. Shalf. The cactus worm: Experiments with dynamic resource discovery and allocation in a grid environment. *Int. J. High Perform. Comput. Appl.*, 15(4):345–358, 2001.
- [7] G. Almes, M. Swamy, and A. Brown. Phoebus. In *SC '06: Proceedings of the 2006 ACM/IEEE conference on Supercomputing*, page 247, New York, NY, USA, 2006. ACM.
- [8] G. Amdahl. Validity of the single processor approach to achieving large scale computing capabilities. In *AFIPS Conference Proceedings*, volume 30, pages 483–485, 1967.

- [9] D. P. Anderson, J. Cobb, E. Korpela, M. Lebofsky, and D. Werthimer. Seti@home: an experiment in public-resource computing. *Commun. ACM*, 45(11):56–61, 2002.
- [10] I. G. Angus, G. C. Fox, J. S. Kim, and D. W. Walker. *Solving problems on concurrent processors: vol. 2*. Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1990.
- [11] O. Aumage, R. Hofman, and H. Bal. Netibis: an efficient and dynamic communication system for heterogeneous grids. In *CCGRID '05: Proceedings of the Fifth IEEE International Symposium on Cluster Computing and the Grid (CCGrid'05) - Volume 2*, pages 1101–1108, Washington, DC, USA, 2005. IEEE Computer Society.
- [12] H. Bal and K. Verstoep. Large-scale parallel computing on grids. *Electronic Notes in Theoretical Computer Science*, 220(2):3 – 17, 2008. Proceedings of the 7th International Workshop on Parallel and Distributed Methods in verification (PDMC 2008).
- [13] P. Bar, C. Coti, D. Groen, T. Herault, V. Kravtsov, M. Swain, and A. Schuster. Running parallel applications with topology-aware grid middleware. In *Fifth IEEE international conference on e-Science and Grid computing: Oxford, United Kingdom*, pages 292–299, Piscataway, NJ, December 2009. IEEE Computer Society.
- [14] J. Barnes and P. Hut. A Hierarchical  $O(N \log N)$  Force-Calculation Algorithm. *Nature*, 324:446–449, December 1986.
- [15] J. Basney, M. Humphrey, and V. Welch. The myproxy online credential repository. *Software: Practise and Experience*, 35(9):801–816, 2005.
- [16] H. Baumgardt, D. C. Heggie, P. Hut, and J. Makino. Parameters of core collapse. *MNRAS*, 341:247–250, May 2003.
- [17] D. Beazley. Swig: an easy to use tool for integrating scripting languages with c and c++. In *TCLTK'96: Proceedings of the 4th conference on USENIX Tcl/Tk Workshop, 1996*, pages 15–15, Berkeley, CA, USA, 1996. USENIX Association.
- [18] R. G. Belleman, J. Bédorf, and S. F. Portegies Zwart. High performance direct gravitational N-body simulations on graphics processing units II: An implementation in CUDA. *New Astronomy*, 13:103–112, February 2008.
- [19] P. Berczik, D. Merritt, R. Spurzem, and H.-P. Bischof. Efficient Merger of Binary Supermassive Black Holes in Nonaxisymmetric Galaxies. *ApJL*, 642:L21–L24, May 2006.
- [20] M. J. Berger and J. Olinger. Adaptive Mesh Refinement for Hyperbolic Partial Differential Equations. *Journal of Computational Physics*, 53:484–512, March 1984.

- [21] Hans Blom. Report on preliminary tcp and udp tests for cosmogrid: <http://castle.strw.leidenuniv.nl/~derek/cgtests/>.
- [22] D. Cameron, L. Guy, Kunszt. P., G. Mccance, H. Stockinger, K. Stockinger, W. Bell, I. Ben-akiva, R. Chytracek, A. Domenici, F. Donno, W. Hoschek, E. Laure, L. Lucio, P. Millar, B. Segal, and M. Sil. Replica management in the european datagrid project. *Journal of Grid Computing*, 2:341–351, 2004.
- [23] H. J. Curnow and B. A. Wichmann. A synthetic benchmark. *The Computer Journal*, 19(1):43–49, 1976.
- [24] DAS-3. The distributed ascii supercomputer 3: <http://www.cs.vu.nl/das3/>.
- [25] DEISA. Distributed european infrastructure for supercomputing applications: <http://www.deisa.eu>.
- [26] A. Denis, C. Perez, and T. Priol. PadicoTM: An open integration framework for communication middleware and runtimes. *Future Generation Computer Systems*, 19(4):575–585, May 2003.
- [27] E. N. Dorband, M. Hemsendorf, and D. Merritt. Systolic and hyper-systolic algorithms for the gravitational n-body problem, with an application to brownian motion. *J. Comput. Phys.*, 185(2):484–511, 2003.
- [28] J. Dunkley, E. Komatsu, M. R. Nolta, D. N. Spergel, D. Larson, G. Hinshaw, L. Page, C. L. Bennett, B. Gold, N. Jarosik, J. L. Weiland, M. Halpern, R. S. Hill, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, E. Wollack, and E. L. Wright. Five-Year Wilkinson Microwave Anisotropy Probe Observations: Likelihoods and Parameters from the WMAP Data. *ApJS*, 180:306–329, February 2009.
- [29] E. Fernandez, E. Heymann, and M. Angel Senar. Supporting efficient execution of mpi applications across multiple sites. In *Euro-Par 2006 Parallel Processing*, pages 383–392. Springer, 2006.
- [30] I. Foster. Globus toolkit version 4: Software for service-oriented systems. *Journal of Computer Science and Technology*, 21(4):513–520, 2006.
- [31] I. Foster, C. Kesselman, and S. Tuecke. The Anatomy of the Grid: Enabling Scalable Virtual Organizations. *International Journal of High Performance Computing Applications*, 15(3):200–222, 2001.
- [32] Ian Foster. *Designing and Building Parallel Programs: Concepts and Tools for Parallel Software Engineering*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1995.
- [33] G. C. Fox, M. A. Johnson, G. A. Lyzenga, S. W. Otto, J. K. Salmon, and D. W. Walker. *Solving problems on concurrent processors. Vol. 1: General techniques and regular problems*. Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1988.

- [34] J. Frey, T. Tannenbaum, M. Livny, I. Foster, and S. Tuecke. Condor-g: A computation management agent for multi-institutional grids. *Cluster Computing*, 5:237–246, 2002.
- [35] M. Fujii, M. Iwasawa, Y. Funato, and J. Makino. Evolution of Star Clusters near the Galactic Center: Fully Self-Consistent N-Body Simulations. *ApJ*, 686:1082–1093, October 2008.
- [36] T. Fukushige, J. Makino, and A. Kawai. GRAPE-6A: A Single-Card GRAPE-6 for Parallel PC-GRAPE Cluster Systems. *Publications of the Astronomical Society of Japan*, 57:1009–1021, December 2005.
- [37] E. Gabriel, G. E. Fagg, G. Bosilca, T. Angskun, J. J. Dongarra, J. M. Squyres, V. Sahay, P. Kambadur, B. Barrett, A. Lumsdaine, R. H. Castain, D. J. Daniel, R. L. Graham, and T. S. Woodall. Open MPI: Goals, concept, and design of a next generation MPI implementation. In *Proceedings, 11th European PVM/MPI Users' Group Meeting*, pages 97–104, Budapest, Hungary, September 2004.
- [38] E. Gabriel, M. Resch, T. Beisel, and R. Keller. Distributed computing in a heterogeneous computing environment. In *Recent Advances in Parallel Virtual Machine and Message Passing Interface*, volume 1497 of *Lecture Notes in Computer Science*, pages 180–187. Springer, 1998.
- [39] E. Gaburov, J. Bedorf, and S. Portegies Zwart. A gravitational tree code on graphics processing units: Implementation in cuda. In *submitted to ICCS 2010*, 2010.
- [40] E. Gaburov, S. Harfst, and S. Portegies Zwart. SAPPORO: A way to turn your graphics cards into a GRAPE-6. *New Astronomy*, 14:630–637, October 2009.
- [41] W. George. Impi: Making mpi interoperable. *Journal of Research - National Institute of Standards and Technology*, 105:343–428, 2000.
- [42] R. L. Graham, G. M. Shipman, B. W. Barrett, R. H. Castain, G. Bosilca, and A. Lumsdaine. Open MPI: A high-performance, heterogeneous MPI. In *Proceedings, Fifth International Workshop on Algorithms, Models and Tools for Parallel Computing on Heterogeneous Networks*, Barcelona, Spain, September 2006.
- [43] W. Gropp, E. Lusk, N. Doss, and A. Skjellum. A high-performance, portable implementation of the MPI message passing interface standard. *Parallel Computing*, 22(6):789–828, September 1996.
- [44] Y. Gu and R. L. Grossman. Udt: Udp-based data transfer for high-speed wide area networks. *Computer Networks*, 51(7):1777–1799, May 2007.

- [45] A. Gualandris and D. Merritt. Ejection of Supermassive Black Holes from Galaxy Cores. *ApJ*, 678:780–797, May 2008.
- [46] A. Gualandris, S. Portegies Zwart, and A. Tirado-Ramos. Performance analysis of direct n-body algorithms for astrophysical simulations on distributed systems. *Parallel Computing*, 33(3):159–173, 2007.
- [47] J. Gustafson. Reevaluating amdahl’s law. *Commun. ACM*, 31(5):532–533, 1988.
- [48] A. Guth. Inflationary universe: A possible solution to the horizon and flatness problems. *Phys. Rev. D*, 23(2):347–356, Jan 1981.
- [49] T. Hamada and T. Iitaka. The Chamomile Scheme: An Optimized Algorithm for N-body simulations on Programmable Graphics Processing Units. *ArXiv Astrophysics e-prints*, astro-ph/0703100, March 2007.
- [50] S. Harfst, A. Gualandris, D. Merritt, R. Spurzem, S. Portegies Zwart, and P. Berczik. Performance analysis of direct N-body algorithms on special-purpose supercomputers. *New Astronomy*, 12:357–377, July 2007.
- [51] E. He, J. Alimohideen, J. Eliason, N. Krishnaprasad, J. Leigh, O. Yu, and T. DeFanti. Quanta: a toolkit for high performance data delivery over photonic networks. *Future Generation Computer Systems*, 19(6):919 – 933, 2003.
- [52] E. He, J. Leigh, O. Yu, and T. A. Defanti. Reliable blast udp : predictable high performance bulk data transfer. In *Proceedings. IEEE International Conference on Cluster Computing*, pages 317–324, 2002.
- [53] D. Heggie and P. Hut. *The Gravitational Million-Body Problem: A Multidisciplinary Approach to Star Cluster Dynamics*. Cambridge University Press, Cambridge, UK, February 2003.
- [54] D. C. Heggie and R. D. Mathieu. Standardised Units and Time Scales. In P. Hut and S. L. W. McMillan, editors, *The Use of Supercomputers in Stellar Dynamics*, volume 267 of *Lecture Notes in Physics*, Berlin Springer Verlag, page 233, 1986.
- [55] J. Herrera, E. Huedo, R. Montero, and I. Llorente. A framework for adaptive execution on grids. *Software: Practice and Experience*, 34(7):631–651, 2004.
- [56] J. Herrera, E. Huedo, R. Montero, and I. Llorente. Porting of scientific applications to grid computing on gridway. *Sci. Program.*, 13(4):317–331, 2005.
- [57] R. W. Hockney. The communication challenge for mpp: Intel paragon and meiko cs-2. *Parallel Computing*, 20(3):389 – 398, 1994.
- [58] R. W. Hockney and J. W. Eastwood. *Computer Simulation Using Particles*. New York: McGraw-Hill, 1981, 1981.

- [59] R. W. Hockney and J. W. Eastwood. *Computer simulation using particles*. Bristol: Hilger, 1988, 1988.
- [60] A. G. Hoekstra, S. F. Portegies Zwart, M. Bubak, and P. M. A. Sloot. *Towards Distributed Petascale Computing*, pages 147–159. Chapman and Hall/CRC, 2008.
- [61] A. G. Hoekstra and P. M. A. Sloot. Introducing grid speedup g: A scalability metric for parallel applications on the grid. In P. M. A. Sloot, A. G. Hoekstra, T. Priol, A. Reinefeld, and M. Bubak, editors, *EGC*, volume 3470 of *Lecture Notes in Computer Science*, pages 245–254. Springer, 2005.
- [62] F. Hohl and R. W. Hockney. A Computer Model of Disks of Stars. *Journal of Computational Physics*, 4:306–+, October 1969.
- [63] E. Holmberg. On the Clustering Tendencies among the Nebulae. II. a Study of Encounters Between Laboratory Models of Stellar Systems by a New Integration Procedure. *ApJ*, 94:385–395, November 1941.
- [64] Huygens. Dutch national supercomputer huygens: <https://subtrac.sara.nl/userdoc/wiki/huygens/description>.
- [65] T. Ishiyama, T. Fukushige, and J. Makino. GreeM : Massively Parallel TreePM Code for Large Cosmological N-body Simulations. *accepted by Publications of the Astronomical Society of Japan*, October 2009.
- [66] T. Ishiyama, T. Fukushige, and J. Makino. Variation of the Subhalo Abundance in Dark Matter Halos. *ApJ*, 696:2115–2125, May 2009.
- [67] K. A. Iskra, F. van der Linden, Z. W. Hendrikse, B. J. Overeinder, G. D. van Albada, and P. M. A. Sloot. The implementation of dynamite: an environment for migrating pvm tasks. *SIGOPS Oper. Syst. Rev.*, 34(3):40–55, 2000.
- [68] K. Jackson. pyglobus: a python interface to the globus toolkit. *Concurrency and Computation: Practice and Experience*, 14:1075–1084, 2002.
- [69] M. Joyce and B. Marcos. Quantification of discreteness effects in cosmological  $n$ -body simulations. ii. evolution up to shell crossing. *Phys. Rev. D*, 76(10):103505, Nov 2007.
- [70] N. Karonis, B. Toonen, and I. Foster. Mpich-g2: A grid-enabled implementation of the message passing interface. *Journal of Parallel and Distributed Computing*, 63(5):551 – 563, 2003. Special Issue on Computational Grids.
- [71] J. Kepler, C. Ptolemaeus, and R. Fludd. *Harmonices mvndi libri v. quorum primus geometricus, de figurarum regularium, quae proportionibus harmonicas constituunt, ortu & demonstrationibus, secundus architectonicus, SEU EX geometria figurata, de figurarum regularium congruentia in plano vel solido: tertius proprie harmonicus, de proportionum harmonicarum ortu EX figuris*. Kepler, J., Ptolemaeus, C., & Fludd, R., 1619.

- [72] V. V. Korkhov, V. V. Krzhizhanovskaya, and P. M. A. Sloot. A grid-based virtual reactor: Parallel performance and adaptive load balancing. *J. Parallel Distrib. Comput.*, 68(5):596–608, 2008.
- [73] K. Kurowski, W. de Back, W. Dubitzky, L. Gulys, G. Kampis, M. Mamonski, G. Szemes, and M. Swain. Complex system simulations with qoscosgrid. In *Computational Science ICCS 2009*, pages 387–396, Heidelberg, Germany, 2009. Springer Berlin / Heidelberg.
- [74] B. W. Lee and S. Weinberg. Cosmological lower bound on heavy-neutrino masses. *Physical Review Letters*, 39:165–168, July 1977.
- [75] G. Lemaître. Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques. *Annales de la Societe Scietifique de Bruxelles*, 47:49–59, 1927.
- [76] G. Lienhart, A. Kugel, and Manner R. Using floating-point arithmetic on fpgas to accelerate scientific n-body simulations. *fccm*, 00:182, 2002.
- [77] Louhi. Csc supercomputer louhi: <http://www.csc.fi/english/pages/deisa/louhi>.
- [78] B. Ludscher, I. Altintas, C. Berkley, D. Higgins, E. Jaeger, M. Jones, E. Lee, J. Tao, and Y. Zhao. Scientific workflow management and the kepler system. *Concurrency and Computation: Practice and Experience*, 18(10):1039–1065, 2006.
- [79] J. MacLaren. Harc: The highly-available resource co-allocator. In *On the Move to Meaningful Internet Systems 2007: CoopIS, DOA, ODBASE, GADA, and IS*, pages 1385–1402, Heidelberg, Germany, 2009. Springer Berlin / Heidelberg.
- [80] A.-M. Madigan, Y. Levin, and C. Hopman. A New Secular Instability of Eccentric Stellar Disks around Supermassive Black Holes, with Application to the Galactic Center. *ApJL*, 697:L44–L48, May 2009.
- [81] J. Makino. Optimal order and time-step criterion for Aarseth-type N-body integrators. *ApJ*, 369:200–212, March 1991.
- [82] J. Makino. Treecode with a Special-Purpose Processor. *Publications of the Astronomical Society of Japan*, 43:621–638, August 1991.
- [83] J. Makino. An efficient parallel algorithm for  $O(N^2)$  direct summation method and its variations on distributed-memory parallel machines. *New Astronomy*, 7:373–384, October 2002.
- [84] J. Makino. A Fast Parallel Treecode with GRAPE. *Publications of the Astronomical Society of Japan*, 56:521–531, June 2004.
- [85] J. Makino and S. J. Aarseth. On a Hermite integrator with Ahmad-Cohen scheme for gravitational many-body problems. *Publications of the Astronomical Society of Japan*, 44:141–151, April 1992.



- [86] J. Makino, T. Fukushige, M. Koga, and K. Namura. GRAPE-6: Massively-Parallel Special-Purpose Computer for Astrophysical Particle Simulations. *Publications of the Astronomical Society of Japan*, 55:1163–1187, December 2003.
- [87] J. Makino, K. Hiraki, and M. Inaba. Grape-dr: 2-pflops massively-parallel computer with 512-core, 512-gflops processor chips for scientific computing. In *SC '07: Proceedings of the 2007 ACM/IEEE conference on Supercomputing*, pages 1–11, New York, NY, USA, 2007. ACM.
- [88] J. Makino, E. Kokubo, and T. Fukushige. Performance evaluation and tuning of grape-6 - towards 40 "real" tflops. *sc*, 00:2, 2003.
- [89] S. Manos, M. Mazzeo, O. Kenway, P. V. Coveney, N. T. Karonis, and B. R. Toonen. Distributed mpi cross-site run performance using mpig. In *HPDC*, pages 229–230, 2008.
- [90] S. L. W. McMillan. The use of supercomputers in stellar dynamics; proceedings of the workshop, institute for advanced study, princeton, nj, june 2-4, 1986. In P. Hut and S. L. W. McMillan, editors, *The Use of Supercomputers in Stellar Dynamics*, volume 267 of *Lecture Notes in Physics*, Berlin Springer Verlag, page 156, 1986.
- [91] R. H. Miller. Gravitational n-body calculation in a discrete phase space. *Journal of Computational Physics*, 6(3):449 – 472, 1970.
- [92] R. H. Miller and K. H. Prendergast. Stellar Dynamics in a Discrete Phase Space. *ApJ*, 151:699–+, February 1968.
- [93] J. J. Monaghan. Smoothed particle hydrodynamics. *ARA&A*, 30:543–574, 1992.
- [94] F. Mueller. A library implementation of posix threads under unix. In *Proceedings of the USENIX Conference*, pages 29–41, 1993.
- [95] A. Nascimento, A. Sena, C. Boeres, and V. Rebello. Distributed and dynamic self-scheduling of parallel mpi grid applications: Research articles. *Concurr. Comput. : Pract. Exper.*, 19(14):1955–1974, 2007.
- [96] K. Nitadori and J. Makino. Sixth- and eighth-order Hermite integrator for N-body simulations. *New Astronomy*, 13:498–507, October 2008.
- [97] K. Nitadori, J. Makino, and P. Hut. Performance tuning of N-body codes on modern microprocessors: I. Direct integration with a hermite scheme on x86\_64 architecture. *New Astronomy*, 12:169–181, December 2006.
- [98] M. Norman, P. Beckman, G. Bryan, J. Dubinski, D. Gannon, L. Hernquist, K. Keahey, J. Ostriker, J. Shalf, J. Welling, and S. Yang. Galaxies Collide On the I-Way: an Example of Heterogeneous Wide-Area Collaborative Supercomputing.

*International Journal of High Performance Computing Applications*, 10(2-3):132–144, 1996.

- [99] NVidia. Geforce gtx285.
- [100] P. Ocvirk, C. Pichon, and R. Teyssier. Bimodal gas accretion in the Horizon-MareNostrum galaxy formation simulation. *MNRAS*, 390:1326–1338, November 2008.
- [101] J. Palmer. The intel®8087 numeric data processor. In *ISCA '80: Proceedings of the 7th annual symposium on Computer Architecture*, pages 174–181, New York, NY, USA, 1980. ACM.
- [102] H. B. Perets, A. Gualandris, G. Kuzi, D. Merritt, and T. Alexander. Dynamical Evolution of the Young Stars in the Galactic Center: N-body Simulations of the S-Stars. *ApJ*, 702:884–889, September 2009.
- [103] H. C. Plummer. On the problem of distribution in globular star clusters. *MNRAS*, 71:460–470, March 1911.
- [104] S. Portegies Zwart, T. Ishiyama, D. Groen, K. Nitadori, J. Makino, C. de Laat, S. McMillan, K. Hiraki, S. Harfst, and P. Grosso. Simulating the universe on an intercontinental grid of supercomputers. *IEEE Computer (accepted)*, 2009.
- [105] S. Portegies Zwart, S. McMillan, D. Groen, A. Gualandris, M. Sipior, and W. Vermin. A parallel gravitational N-body kernel. *New Astronomy*, 13:285–295, July 2008.
- [106] S. Portegies Zwart, S. McMillan, S. Harfst, D. Groen, M. Fujii, B. Ó Nualláin, E. Glebbeek, D. Heggie, J. Lombardi, P. Hut, V. Angelou, S. Banerjee, H. Belkus, T. Fragos, J. Fregeau, E. Gaburov, R. Izzard, M. Juric, S. Justham, A. Sottoriva, P. Teuben, J. van Bever, O. Yaron, and M. Zemp. A multiphysics and multiscale software environment for modeling astrophysical systems. *New Astronomy (in press)*, 14:369–378, May 2009.
- [107] S. F. Portegies Zwart, H. Baumgardt, P. Hut, J. Makino, and S. L. W. McMillan. Formation of massive black holes through runaway collisions in dense young star clusters. *Nature*, 428:724–726, April 2004.
- [108] S. F. Portegies Zwart, R. G. Belleman, and P. M. Geldof. High-performance direct gravitational N-body simulations on graphics processing units. *New Astronomy*, 12:641–650, November 2007.
- [109] S. F. Portegies Zwart and S. L. W. McMillan. The Runaway Growth of Intermediate-Mass Black Holes in Dense Star Clusters. *ApJ*, 576:899–907, September 2002.

- [110] S. F. Portegies Zwart, S. L. W. McMillan, P. Hut, and J. Makino. Star cluster ecology - IV. Dissection of an open star cluster: photometry. *MNRAS*, 321:199–226, February 2001.
- [111] S. F. Portegies Zwart, S. L. W. McMillan, and J. Makino. Star cluster ecology - VII. The evolution of young dense star clusters containing primordial binaries. *MNRAS*, 374:95–106, January 2007.
- [112] T. J. Pratt, L. G. Martinez, M. O. Vahle, and T. V. Archuleta. Sandia’s network for supercomputer ‘96: Linking supercomputers in a wide area asynchronous transfer mode (atm) network. Technical report, Sandia National Labs., Albuquerque, NM (United States), 1997.
- [113] S. Prunet, C. Pichon, D. Aubert, D. Pogosyan, R. Teyssier, and S. Gottloeber. Initial Conditions For Large Cosmological Simulations. *ApJS*, 178:179–188, October 2008.
- [114] L. Qiu, Y. Zhang, and S. Keshav. On individual and aggregate tcp performance. In *Network Protocols, 1999. (ICNP ’99) Proceedings. Seventh International Conference on*, pages 203–212, August 2002.
- [115] E. E. Salpeter. The Luminosity Function and Stellar Evolution. *ApJ*, 121:161, January 1955.
- [116] K. Schwarzschild. On the Gravitational Field of a Mass Point According to Einstein’s Theory. *Abh. Konigl. Preuss. Akad. Wissenschaften Jahre 1906,92, Berlin,1907*, pages 189–196, 1916.
- [117] L. Smarr, T. DeFanti, M. Brown, and C. de Laat. Special section: igrid 2005: The global lambda integrated facility. *Future Generation Computer Systems*, 22(8):849 – 851, 2006.
- [118] M. Snir, S. W. Otto, D. W. Walker, J. Dongarra, and S. Huss-Lederman. *MPI: The Complete Reference*. MIT Press, Cambridge, MA, USA, 1995.
- [119] D. N. Spergel, R. Bean, O. Doré, M. R. Nolta, C. L. Bennett, J. Dunkley, G. Hinshaw, N. Jarosik, E. Komatsu, L. Page, H. V. Peiris, L. Verde, M. Halpern, R. S. Hill, A. Kogut, M. Limon, S. S. Meyer, N. Odegard, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright. Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology. *ApJS*, 170:377–408, June 2007.
- [120] V. Springel, S. D. M. White, A. Jenkins, C. S. Frenk, N. Yoshida, L. Gao, J. Navarro, R. Thacker, D. Croton, J. Helly, J. A. Peacock, S. Cole, P. Thomas, H. Couchman, A. Evrard, J. Colberg, and F. Pearce. Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature*, 435:629–636, June 2005.

- [121] C. Stewart, R. Keller, R. Repasky, M. Hess, D. Hart, M. Muller, R. Sheppard, U. Wossner, M. Aumuller, H. Li, D. Berry, and J. Colbourne. A global grid for analysis of arthropod evolution. In *GRID '04: Proceedings of the 5th IEEE/ACM International Workshop on Grid Computing*, pages 328–337, Washington, DC, USA, 2004. IEEE Computer Society.
- [122] E. Strömngren. Ein numerisch gerechneter Spezialfall des Dreikörper problems mit Massen und Distanzen von derselben Größenordnung. *Astronomische Nachrichten*, 182:181–187, September 1909.
- [123] D. Sugimoto, Y. Chikada, J. Makino, T. Ito, T. Ebisuzaki, and M. Umemura. A Special-Purpose Computer for Gravitational Many-Body Problems. *Nature*, 345:33–35, May 1990.
- [124] X. Sun and L. Ni. Scalable problems and memory-bounded speedup. *J. Parallel Distrib. Comput.*, 19(1):27–37, 1993.
- [125] A. Takefusa, H. Nakada, T. Kudoh, Y. Tanaka, and S. Sekiguchi. Gridars: An advance reservation-based grid co-allocation framework for distributed computing and network resources. In *Job Scheduling Strategies for Parallel Processing*, pages 152–168, Heidelberg, Germany, 2008. Springer Berlin / Heidelberg.
- [126] T. S. van Albada. Numerical integrations of the N-body problem. *Bulletin of the Astronomical Institutes of the Netherlands*, 19:479–499, jan 1968.
- [127] R. van Nieuwpoort, J. Maassen, G. Wrzesinska, R. Hofman, C. Jacobs, T. Kielmann, and H. Bal. Ibis: a flexible and efficient Java based grid programming environment. *Concurrency and Computation: Practice and Experience*, 17(7-8):1079–1107, June 2005.
- [128] E. Vesperini and D. C. Heggie. On the effects of dynamical evolution on the initial mass function of globular clusters. *MNRAS*, 289:898–920, August 1997.
- [129] E. Vesperini, S. L. W. McMillan, and S. Portegies Zwart. Effects of Primordial Mass Segregation on the Dynamical Evolution of Star Clusters. *ApJ*, 698:615–622, June 2009.
- [130] S. von Hoerner. Die numerische Integration des n-Körper-Problemes für Sternhaufen. I. *Zeitschrift für Astrophysik*, 50:184–214, 1960.
- [131] V. Welch, I. Foster, C. Kesselman, O. Mulmo, L. Pearlman, J. Gawor, S. Meder, and F. Siebenlist. X.509 proxy certificates for dynamic delegation. In *Proceedings of the 3rd Annual PKI R&D Workshop*, 2004.
- [132] G. Wrzesińska, R. van Nieuwpoort, J. Maassen, and H. Bal. Fault-tolerance, malleability and migration for divide-and-conquer applications on the grid. In *IPDPS '05: Proceedings of the 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS'05) - Papers*, page 13.1, Washington, DC, USA, 2005. IEEE Computer Society.

- [133] G. Xu. A New Parallel N-Body Gravity Solver: TPM. *ApJS*, 98:355–366, May 1995.
- [134] K. Yoshikawa and T. Fukushige. PPPM and TreePM Methods on GRAPE Systems for Cosmological N-Body Simulations. *Publications of the Astronomical Society of Japan*, 57:849–860, December 2005.
- [135] P. Young, J. E. Gunn, J. B. Oke, J. A. Westphal, and J. Kristian. Q0957+561 - Detailed models of the gravitational lens effect. *ApJ*, 244:736–755, March 1981.
- [136] J. Yu and R. Buyya. A taxonomy of workflow management systems for grid computing. *Journal of Grid Computing*, 3:171–200, 2005.
- [137] F. Zwicky. Nebulae as gravitational lenses. *Phys. Rev.*, 51(4):290, Feb 1937.