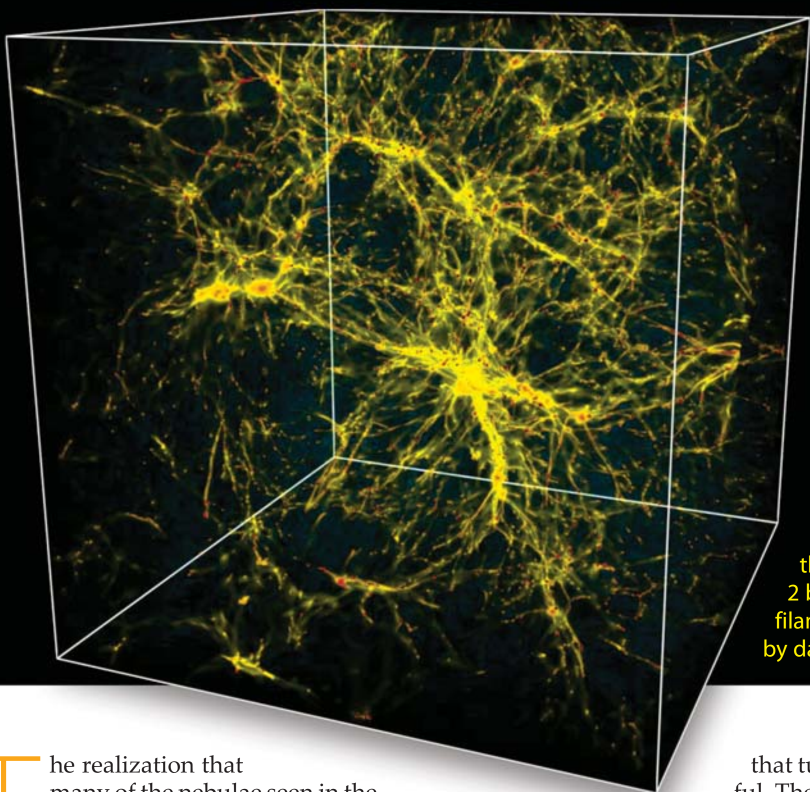
Theoretical challenges in understanding galaxy evolution

Jeremiah P. Ostriker and Thorsten Naab

The concordance cosmological model provides initial conditions and a reliable framework for simulating the evolution of primordial fluctuations into galaxies. But many unsolved problems remain.



Gas is the material basis of galaxy formation. This simulation, a snapshot of the gas component of the universe about 2 billion years after the Big Bang, shows a filamentary structure similar to that displayed by dark matter. (Courtesy of Renyue Cen.)

The realization that many of the nebulae seen in the night sky, including our own neighbor Andromeda (M31), are galaxies, made up of 10^9 to 10^{11} stars, and are similar to our own Milky Way was slow to become accepted, with the final "proof" only reached when Walter Baade resolved individual calibrated stars in M31 during a 1942 wartime blackout. For some time thereafter, they were simply considered to be "there," extragalactic objects that might be used as standard meter sticks or standard candles in cosmological investigations initiated by Edwin Hubble and Allan Sandage to determine the geometry of the universe. Serious investigation of origins, beginning in the 1960s, was prompted by the realization by Beatrice Tinsley that since stars evolve and die, galaxies must evolve, and so cosmological investigations must not treat galaxies as fixed objects but should allow for the necessary evolution.

There was no accepted model for the origin of the perturbations that could have produced the galaxies; thus an ab initio approach was not possible, and the initial work followed two other paths that turned out to be quite fruitful. The first might be considered the archaeological approach (see the article by Anna Frebel and Volker Bromm, Physics Today, April 2012, page 49). Astronomers studied the various components observed in our galaxy and other nearby systems, developed techniques to estimate the typical ages of formation and chemical composition of the stars in those components, and attempted to reconstruct the history of the systems that would result in what we see today. It appears, from a detailed study of the disk, that this component grew slowly in size and mass as rotationally supported gas was steadily turned into stars over cosmic time and that the typical stars in our cosmic neighborhood were formed only 3 billion to 6 billion years ago, relatively late in the evolution of the universe. In contrast, the stars in the extended spheroidal component, or in an elliptical

Jeremiah Ostriker is a professor in the department of astrophysical sciences at Princeton University in Princeton, New Jersey. **Thorsten Naab** is a research group leader at the Max Planck Institute for Astrophysics in Garching, Germany.

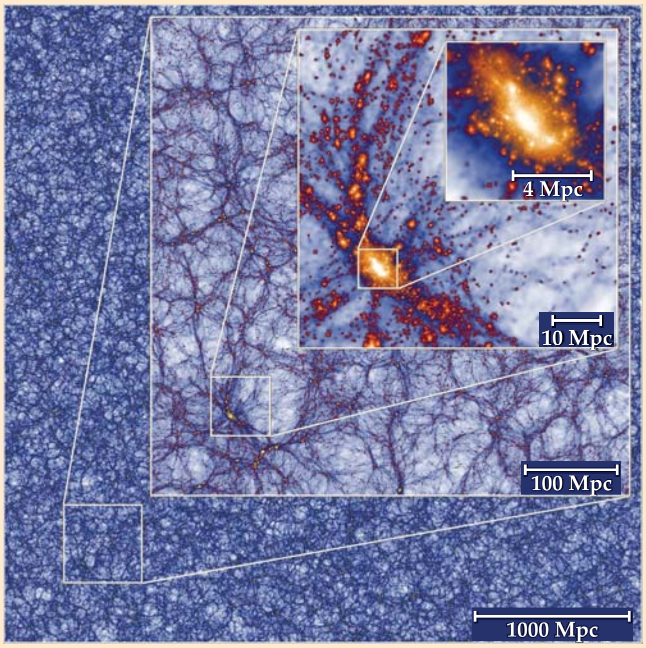


Figure 1. The cosmic web. Dark-matter distribution in a slice of 8 megaparsecs predicted from the Millennium XXL simulation within a box of 4.1-Gpc side length. At present, this simulation is the largest of its kind, with more than 300 billion particles. (Courtesy of Raul Angulo, Volker Springel, and Simon White; see also ref. 3.)

galaxy, were found to be typically 10 billion to 15 billion years old and lower in the abundances that they had of heavy elements, and they tended to have an isotropic or even somewhat radially biased distribution of orbits.

So, a picture developed that infalling gas clouds at early cosmic epochs condensed into the stars that we see in the spheroid and encompassing stellar halo; this skeleton remained to the present time, perhaps somewhat augmented by later infalling satellite systems, to tell of the early history of our galaxy. Other elliptical systems observed in detail, though more massive and richer in metals (elements heavier than helium) than the spheroid of the Milky Way, seemed to be composed of stars of similar age and orbital properties, so it was plausible that they formed by a similar process. The disk was a later addition as higher-angular-momentum material drifted into the galaxy, accumulated in a rotating disk, and was gradually turned into the bulk of the stars in our system. While the details of the archaeological approach have evolved, the overall picture has withstood the test of time remarkably well. The archaeological approach to galaxy formation and evolution continues, with much useful work being done to tease out the details of how the extended spheroidal component was put into place.

The second approach was more physics based. Simple questions were asked about how objects of the size and mass of normal galaxies could be made. Three influential papers published in 1977 showed that there was a characteristic mass that could be expressed in terms of the fundamental constants that seemed relevant to galaxy formation:

$$M \approx \left[\left(\frac{Gm_\mathrm{p}^2}{\hbar c}\right)^{-2}\left(\frac{e^2}{\hbar c}\right)^{5}\left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^{1/2}\right] m_\mathrm{p},$$

which is roughly 10^{12} solar masses ($M_\odot$).[1] Here e is the electron charge and m_p and m_e are the proton and electron masses.

Objects with a mass much larger than M have difficulty cooling their gas, and their collapse to stellar systems is impaired. That expectation is borne out in nature, since individual galaxies rarely exceed M, while many giant gas- and dark-matter-dominated systems—for example, clusters of galaxies—exist far above this limit, where the fraction of the baryons that collapsed into stars is small.

In the same time frame of the late 1970s and the 1980s, explorations of several other simple physics problems led to a growth of our understanding. Starting from the first self-consistent merger simulations by Simon White in 1978, White and other modelers explored the consequences of interactions and mergers of spheroidal galaxies and disk galaxies—rare but spectacular events detected in many surveys—and showed how those might lead to bursts of star formation and the transformation of spiral galaxies to more featureless, elliptical-like systems. Lyman Spitzer and Baade showed how higher-speed collisions could strip galaxies of gas and potentially transform spirals to "S0" systems that don't have spiral arms, and one of us (Ostriker) and colleagues looked at dynamical friction, a phenomenon codified by Subrahmanyan Chandrasekhar wherein massive objects spiral toward the center of a potential well as they lose energy and are pulled back along their orbits by the gravitational forces of the matter collected in their wakes. Dynamical friction is of major importance for massive galaxies that can thereby consume their satellites (via "cannibalism," or minor mergers) and consequently grow significantly in size and mass without further star formation.

The study of those and other toy problems did not and could not solve the problem of galaxy formation but did help to illuminate several of the physical processes that must occur during galaxy formation. By the end of the 1980s, theories for the development of cosmic structure from a spectrum of ab initio perturbations were beginning to be developed. Two separate schools, one based on Yakov Zeldovich in Moscow and one based on James Peebles in Princeton, New Jersey, had shown, in the linear domain, how very small perturbations could grow via gravitational instabilities, but carrying the calculations to the extreme nonlinear limits required for galaxy formation was far beyond the computational capabilities of the period.

Numerous puzzles were left standing at the end of that time. Do massive galaxies form early or late? On the one hand, the archaeological approach indicated, by direct measurements, that they were primarily composed of old, low-mass stars and seemed to have an age comparable to the age of the universe, in contrast to spiral and many dwarf systems that have ongoing star formation and a substantial young stellar population. But the developing theories of structure formation unequivocally predicted that low-mass self-gravitating objects form first and more massive systems form later. Then, when dark-matter simulations reached the degree of sophistication to allow a quantitative characterization of halo properties and statistics (as, for example, in the work of the "gang of four": Marc Davis, George Efstathiou, Carlos Frenk, and White),[2] the question immediately arose as to why the mass distribution of dark-matter halos was so different from the mass distribution observed in galaxies. And why was the dark-matter density detected in the centers of galaxies so much less than would have been expected from simple scaling arguments? The questions were endless and could not be addressed by adding to the repertoire of toy problems that concentrated on one or another of the individual physical processes. A more systematic and global approach was required.

The modern paradigm

After the discovery of the cosmic microwave background (CMB) radiation fluctuations by the *Cosmic Background Explorer* satellite in 1992, an orderly approach to the problem of when and how galaxies grew from a nearly uniform background became possible. The fluctuations seen on the sky with a relative amplitude of about 10^{-5} would grow to nonlinear amplitudes by recent epochs via straightforward gravitational instabilities, especially with the boost offered by the roughly 6:1 preponderance of the (by this point established) dark-matter component of the cosmos.

By the late 1990s, the preponderance of dark energy had also been established, and the *Wilkinson Microwave Anisotropy Probe* (launched in 2001) satellite team combined the CMB results with other accumulating data and produced a definitive cosmological model. In that concordance cosmological model, 74% of the universe is made of dark energy and only 26% is matter. The baryonic matter, out of which interstellar gas, stars, and galaxies are made, only contributes, overall, a small fraction, 4.5%, which is 16% of the total matter content. The rest of the matter, $5/6$ of the total, is gravitating but not emitting or absorbing radiation and was therefore coined dark matter.

The concordance model is now well tested and strongly supported by detailed investigations using many different indicators. Those include use of supernova-determined distances to directly measure the rate of change of the expansion rate, of the detailed spatial spectrum of the CMB radiation, and of gravitational lensing. As of the present time, the overall parameters of the model are determined to several-percent accuracy with no significant inconsistencies having been identified. There remain some puzzles at small scales and low redshift, but, overall, the agreement between observations and the model can only be called uncanny. What is of special significance for those of us studying galactic formation and evolution is that the concordance model appears to give us the rather precise and testable initial conditions for the growth of perturbations.

Simulations of dark-matter structure

With the help of the well-constrained initial conditions provided by the concordance model, the

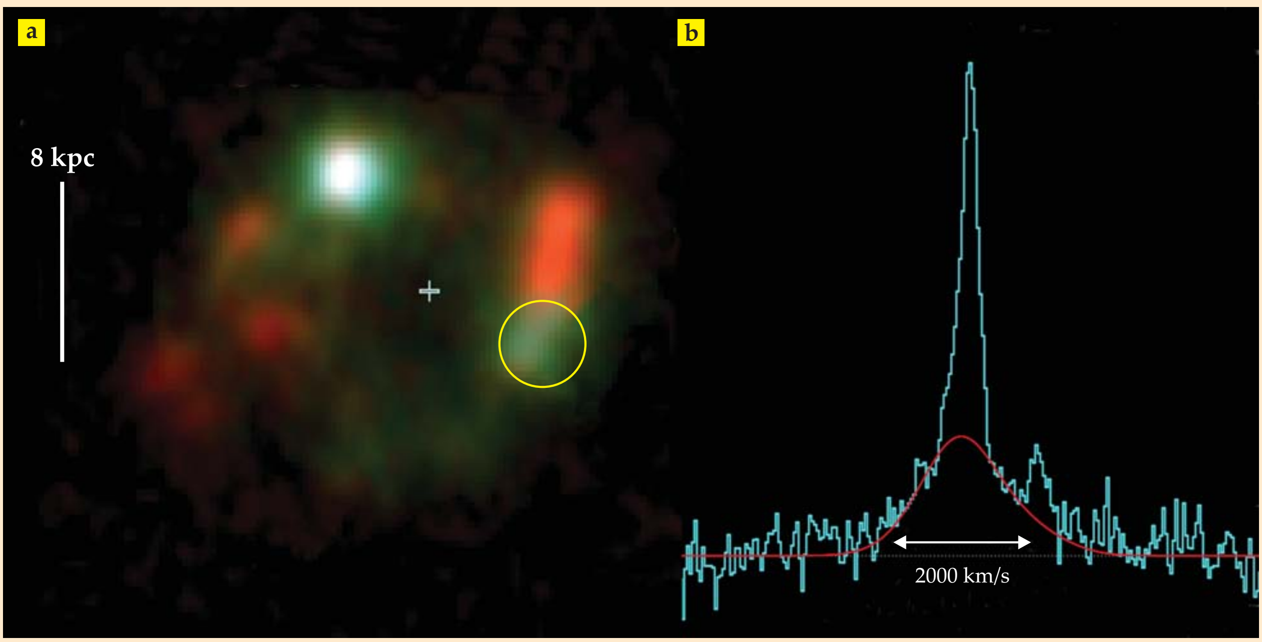


Figure 2. Adaptive-optics-assisted observations. (a) Star-forming clumps in ZC406690, a galaxy that is forming stars at a rate of 100 solar masses per year about 4 billion years after the Big Bang. The circled star-forming region yielded the hydrogen-alpha (656 nm) emission-line spectrum seen in **(b)**. The broad wings in the emission-line profiles indicate strong outflows of several thousand kilometers per second. Only the first steps have been made to simulate galaxies like this in a full cosmological context. (Adapted from ref. 4; courtesy of Sarah Newman and Reinhard Genzel.)

evolution of dark-matter structure can now be investigated to unprecedented detail on cosmological scales up to several gigaparsecs with high-performance simulations on modern supercomputers. The picture we derive from those simulations is as follows (see also the article by Tom Abel, PHYSICS TODAY, April 2011, page 51). Approximately 300 000 years after the Big Bang, when the light carrying the information about the CMB was sent out, the dark matter was almost homogenously distributed with only small fluctuations at roughly one part in 10^5. Subsequently, the relative amplitudes grew, and complex structures developed within the dark-matter component; the regions having the most negative gravitational potential became self-gravitating and collapsed into small individual halos. The dark-matter halos grew by accretion of dark matter and by mergers with other, smaller halos embedded in a cosmic web of dark matter. Computer simulations of this process (see figure 1) now make clear predictions about the sizes, masses, and spatial distribution of dark-matter halos at any time in cosmic history,[3] with independent groups arriving at concordant results.

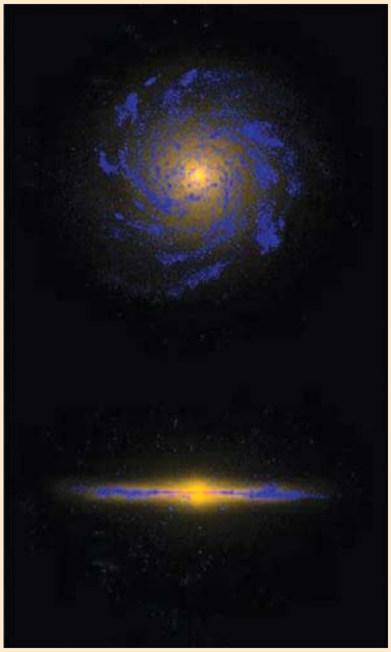


Figure 3. A spiral galaxy with a realistic thin disk structure of old (yellow) and young (blue) stars simulated at high numerical resolution. (Courtesy of Javiera Guedes; adapted from ref. 12.)

But what of the baryonic component, the normal matter? With the advent of large samples of observed galaxies like the Sloan Digital Sky Survey, it became possible to match galaxy populations to the populations of simulated dark-matter halos using the simple assumptions that every halo hosts a galaxy at its center and that more massive galaxies live in more massive halos and then insisting that the spatial distribution of galaxies be reproduced correctly.

A typical galaxy with a stellar mass similar to the Milky Way ($5 \times 10^{10}\ M_\odot$) lives in a dark-matter halo of $10^{12}\ M_\odot$. With the cosmic ratio of baryons to dark matter being 1/5, as determined by precise CMB measurements, a halo of that mass might have been expected to host a central galaxy containing $2 \times 10^{11}\ M_\odot$ of baryons. But, just as in the Milky Way, the central galaxy (including both its observable stellar and gas components) is only 25% of that amount—a smaller fraction than expected. The fraction can be labeled the galaxy-formation efficiency. Some processes have clearly impeded the collapse of gas into stars or reversed the collapse phase, ejecting the infalling gas back into the surrounding dark-matter halo.

Particularly startling was the finding that less massive halos, which typically host lower-mass spiral galaxies and dwarf galaxies, convert an even smaller fraction of gas into stars, with galaxy-formation efficiencies dropping to only a few percent. The conclusion must be that in systems spanning several orders of magnitude in mass, important physical processes have prevented the gas either from cooling or from forming stars; alternatively, residual gas was expelled from systems by feedback processes.

During the past decade, high-resolution observations of high-redshift galaxies, initiated by Charles Steidel, Max Pettini, and many others, have revealed surprising insights into what might have happened to the gas that was not converted into stars. In the early universe, star-forming galaxies at look-back times of 10 billion years and more (that is, viewed as they were 10 billion or more years ago) are seen to be expelling large amounts of gas in galactic winds at rates that can be several times higher than the rate at which gas is being transformed into stars. At somewhat lower redshifts, with the use of adaptive optics, Reinhard Genzel and collaborators have traced the origin of those winds to individual kiloparsec-sized star-formation regions with extreme gas densities embedded in the disks (and nuclei) of gas-rich star-forming galaxies;[4] see figure 2.

We have known for decades that lines of sight to distant quasars passing within 50–100 kpc of normal galaxies traverse metal-enriched gas clouds surrounding those systems. Presumably, the origins of that metal-enriched gas are in the winds, seen by Steidel and others, emanating from the star-forming galaxies at speeds comparable to the escape velocity from the observed galaxies. If that expulsion process were efficient enough, it would serve as a natural explanation for the apparently inefficient conversion of gas into stars. In addition to returning gas to the surrounding gaseous envelopes, those winds would shock-heat the ambient fluid, making it more difficult for the gas to cool and collapse inward. Moreover, from x-ray observations we know of rich clusters of galaxies, such as the Coma cluster, that contain massive amounts of metal-rich, thermally emitting gas (with a temperature of roughly 10^8 K), which has presumably been expelled from the galaxies, with metal content roughly equal to the metal content in the stellar components of the embedded galaxies. Thus observations suggest that during episodes of high star formation within galaxies, winds driven by the mechanical and radiant output of stars and supernovae blow out a significant fraction of the gas and the embedded heavy elements.

Development of gas-dynamical simulations

The understanding and modeling of the physical processes that control the formation and evolution of stars and their interaction with the interstellar medium, and that therefore govern galaxy formation, pose major theoretical challenges for astrophysicists all over the world who work on galaxy formation. The advent of modern, parallel supercomputers and highly efficient numerical algorithms allowed us to treat the formation of cosmic structure in large cosmological volumes as well as the dynamics of individual galaxies on parsec scales in unprecedented detail.

Three quite independent and complementary approaches have been followed, which we might label the semianalytic, the global, and the zoom approaches. The widely utilized semianalytic approach, suggested by White and Martin Rees,[5] is based on the combination of galaxy-formation modeling with both the theory of structure growth and dark-matter simulations, which have now reached a state where computations allow both an accurate global description on cosmological scales and quite detailed characterization of millions of individual dark-matter halos.[6] Estimates are made of how gas-dynamical processes would lead to the formation of the individual galaxies that would populate those halos, with uncertain parameters adjusted to fit improving observations from galaxy surveys at all redshifts. So far this is the only approach allowing a consistent investigation of the evolution of full populations of galaxies over cosmological time scales on small and very large spatial scales. Computationally, the approach is very efficient; however, the treatment of the baryonic component of the universe is approximate and the dynamical evolution of gas and stars is not computed self-consistently. Therefore, no detailed prediction about the internal dynamical galaxy properties is possible. Since adopted parameters are tuned to match the best observations available at any time, assessment of the semianalytic methodology by comparison to observations is difficult.

In the global approach, first applied by August Evrard, the dynamics of the intergalactic medium and the stars is computed together with the evolution of the dark-matter component for a given cosmological model.[7] The focus here is on the when, where, and roughly how of galaxy formation and evolution, with all efforts to understand the detailed modeling of individual galaxies foregone or treated in a very approximate fashion. Various groups established that galaxy formation began at roughly redshift $z = 6$ and that the hot stars in early galaxies were probably responsible for reionizing the hydrogen in the universe; they roughly established how the observed galaxy large-scale structure developed, what processes determined the mass spectrum of galaxies, and approximately how the overall efficiency of transforming baryons into galaxies was established.

Using large-scale cosmological numerical simulations, Dusan Keres and collaborators showed, and a group led by Avishai Dekel using an independent numerical algorithm later confirmed, that cold gas efficiently flows directly into the centers of dark-matter halos along thin filaments—even if the halo is above the critical halo mass, given in the equation on page 44, above which individual galaxy formation becomes difficult and hot gaseous halos are expected to form.[8] With today's powerful supercomputers, the impact of important physical mechanisms like the energy output from massive young stars, supernova explosions, or accreting black holes can now be studied on global scales. This is done with simple subresolution models that describe the physics on scales that cannot be resolved by the simulations.[9] The challenges to be addressed are whether energetic feedback from supernovae and, eventually, accreting black holes (active galactic nuclei) can be responsible for the earlier noted inefficient conversion of gas into stars and the enrichment of the interstellar medium with heavy elements, and whether different galaxy types can be explained. Still, global simulations are computationally expensive and lack the required resolution to accurately model the internal structure of individual galaxies.

The third method, which we have labeled the zoom approach, is one in which particular regions are focused on with greater and greater numerical resolution and physical realism. It was first applied to cosmological galaxy-formation simulations by White and Neal Katz and is now the method of choice to investigate the formation and evolution of individual galaxies in a full cosmological context.[10] With that method, material forming a present-day dark-matter halo is followed back to high redshift when the simulation was started. The high-density concentrations within the region are then represented with considerably

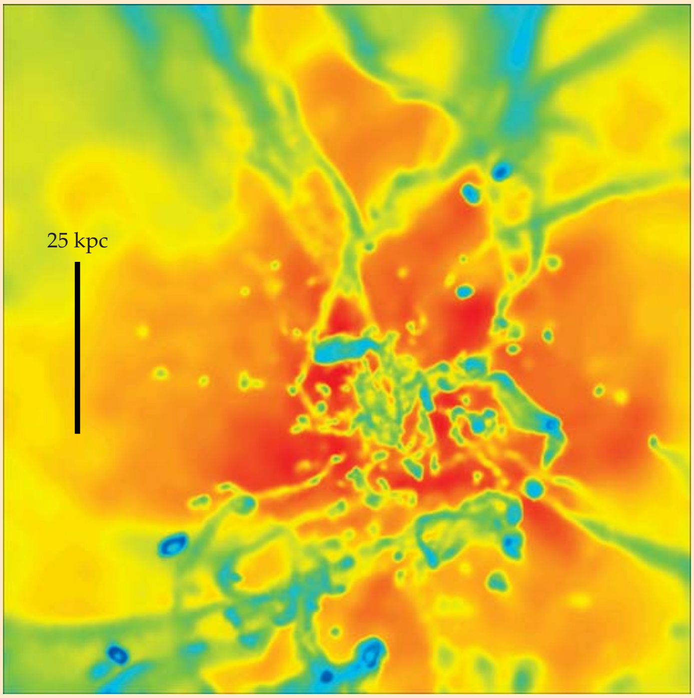


Figure 4. Gas streams. At redshift $z = 3$, gas inflow along cold filaments and clumps (blue) penetrating the forming hot gaseous halo (red) is driving the dissipative formation of the compact core of a massive galaxy. (Courtesy of Peter Johansson.)

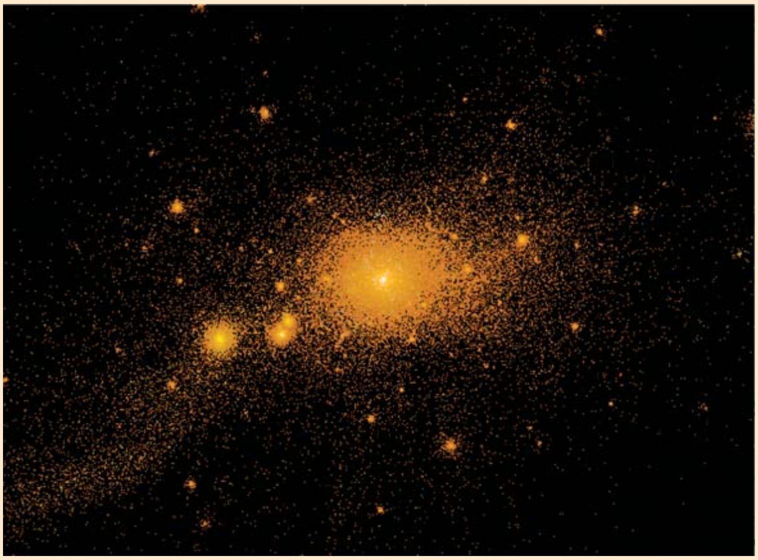


Figure 5. Simulated stellar distribution of a massive galaxy that is in the process of accreting smaller stellar systems in minor mergers.[14] The most massive satellite galaxy is 1/10 as massive as the central galaxy. The stars of the accreted systems assemble in the outer parts of the central galaxy and contribute significantly to its rapid growth over cosmic time.

higher mass and space resolution, and the region's evolution is simulated again. Now gas dynamics is followed self-consistently to small scales, with simple recipes for star formation, resulting in a much better understanding of the internal structure. Several iterations to higher and higher spatial and mass resolution are possible.

Using the zoom method to study the detailed dynamics of gas assembling in the dark-matter halos and the formation of stars and black holes that build the galaxies is numerically very challenging. Not only does a simulation need to resolve more than nine orders of magnitude in space and time, it also needs to accurately treat feedback processes—the ejection of mass, energy, and momentum into the interstellar medium. Two forms of feedback are dominant: The winds, supernovae, and UV from massive stars must be treated properly, and the energy and momentum emitted by central black holes can be very important for massive systems. Understanding both sets of processes is at the forefront of current research.

Even the most advanced cosmological galaxy-formation simulations cannot resolve all relevant feedback processes. All detailed interactions between accreting black holes or newly forming stars and the ambient interstellar medium must be followed by subresolution models that are motivated either by analytical estimates or by specialized small-scale simulations. At present the subresolution feedback models are the weakest spot in modern galaxy-formation simulations, even in the zoom approach. If the treatment of the subgrid processes of star formation and feedback is not accurately motivated, the outcome of the zoom simulations will be inaccurate however high the spatial and mass resolution.

A particularly persistent problem for cosmological simulations is to comprehend the separate existence of disk and spheroidal components and the increasing ratio of spheroidal to disk mass with increasing galaxy mass. Until recently, almost all attempts to simulate the formation and evolution of individual disk galaxies in a full cosmological context have failed. Either the stellar galaxy disks were too small and the galaxies were dominated by a spheroidal bulge component, or, in simulations that did form thin disks, the total mass of the galaxies was too high for the dark-matter halos in which they lived, violating constraints on the known baryon conversion efficiency. More efficient feedback mechanisms, which limit the formation of stars and drive strong outflows, seemed to be destructive to the disk component. A recent success of the zoom approach was the ability to resolve the formation of interstellar medium structure, star formation, and feedback on the scales of giant molecular clouds.[11] That more accurate and realistic treatment—still far from resolving the internal structure of molecular clouds—seems also to result in more realistic simulated spiral galaxies (see figure 3).[12]

High-resolution zoom simulations also shed light on the dominant formation and evolution processes of giant elliptical galaxies. Since those are the most massive stellar systems, they should have assembled only recently. But they are known to contain very old stars, which apparently formed in the early days of the universe. Analyzing a large sample of zoom simulations of massive galaxies, a group led by the authors of this article found indications that massive galaxies probably form in two stages.[13] At high redshift, gas is efficiently funneled into the centers of the forming dark-matter halos in cold streams and builds a dense and small stellar system (see figure 4). After the critical mass given by the equation is reached, shocks propagate outward, enveloping the galaxy in a hot x-ray-emitting gaseous halo. That halo shields the system from cold gas inflows, and star formation declines rapidly. With increasing time, more matter, starting farther away from the galaxies, is accreted. That material, however, already has mostly turned into stars, which then accrete in minor mergers and assemble in the outer parts of the galaxies;[14] see figure 5.

In the first phase, the galaxies are small and their spectrum is dominated by young blue stars formed in situ; in the second phase, the galaxy is accreting old, smaller-mass stellar systems and becomes larger and more red in spectral appearance. Needless to say, the two phases overlap. Also confirmatory is the recent observational work by Pieter van Dokkum and his group, which strongly supports the picture that second-stage growth, fueled by accretion of old, lower-mass systems, has roughly doubled the mass and extended by a factor of four the size of massive elliptical systems over recent cosmic epochs.[15]

The present state of the art shows real success in producing massive elliptical galaxies at the right cosmic epochs, in the right range of masses, of the right size, and in roughly the right abundance. On the minus side, the ratio of galaxy mass to dark-matter halo mass is still uncomfortably large in many of the simulations. Zoom simulations have achieved some recent successes for spiral systems. But they typically have not successfully obtained, for example, correct bulge-to-disk ratios or extended structures with flat rotation curves.

Paradoxically, the failures in simulations are evidence for solid scientific success: Modeling has progressed to the state where it can be wrong! What are the missing physical ingredients? It is likely, from preliminary work under way by several groups, that a more accurate modeling of feedback processes and a better treatment of the multiphase structure of the interstellar medium are the critical additional needed processes. Balancing energy and momentum losses in the interstellar medium with inputs from young stars and supernovae should, in fact, determine the star formation rate without the need for ad hoc prescriptions and also determine the structure of a three-phase interstellar medium.[16] Those same feedback processes, plus the input from physically modeled active galactic nuclei winds, are expected to self-consistently drive the galactic winds that are needed for establishing the bulge-to-disk and galaxy-to-halo mass ratios that are observed.[17] Rapid progress in accurate physical modeling over the next several years is expected to bring us much closer to a quantitative understanding of galaxy morphologies—the Hubble sequence—as seen by the *Hubble Space Telescope* in its Ultra Deep Field view of the universe.

References

1. J. Binney, *Astrophys. J.* **215**, 483 (1977); M. J. Rees, J. P. Ostriker, *Mon. Not. R. Astron. Soc.* **179**, 541 (1977); J. Silk, *Astrophys. J.* **211**, 638 (1977).
2. M. Davis et al., *Astrophys. J.* **292**, 371 (1985).
3. V. Springel et al., *Nature* **435**, 629 (2005); R. E. Angulo et al., http://arxiv.org/abs/1203.3216.
4. R. Genzel et al., *Astrophys. J.* **733**, 101 (2011).
5. S. D. M. White, M. J. Rees, *Mon. Not. R. Astron. Soc.* **183**, 341 (1978).
6. G. Kauffmann, S. D. M. White, B. Guiderdoni, *Mon. Not. R. Astron. Soc.* **264**, 201 (1993).
7. A. E. Evrard, *Mon. Not. R. Astron. Soc.* **235**, 911 (1988).
8. D. Keres et al., *Mon. Not. R. Astron. Soc.* **363**, 2 (2005); A. Dekel et al., *Nature* **457**, 451 (2009). See also S. F. Shandarin, Y. B. Zeldovich, *Rev. Mod. Phys.* **61**, 185 (1989).
9. See, for example, D. Sijacki et al., *Mon. Not. R. Astron. Soc.* **380**, 877 (2007).
10. N. Katz, S. D. M. White, *Astrophys. J.* **412**, 455 (1993).
11. F. Governato et al., *Nature* **463**, 203 (2010); O. Agertz, R. Teyssier, B. Moore, *Mon. Not. R. Astron. Soc.* **410**, 1391 (2011).
12. J. Guedes et al., *Astrophys. J.* **742**, 76 (2011).
13. T. Naab et al., *Astrophys. J.* **658**, 710 (2007).
14. T. Naab, P. H. Johansson, J. P. Ostriker, *Astrophys. J. Lett.* **699**, L178 (2009).
15. P. G. van Dokkum et al., *Astrophys. J.* **709**, 1018 (2010).
16. E. C. Ostriker, C. F. McKee, A. K. Leroy, *Astrophys. J.* **721**, 975 (2010); C. F. McKee, J. P. Ostriker, *Astrophys. J.* **218**, 148 (1977).
17. T. Di Matteo, V. Springel, L. Hernquist, *Nature* **433**, 604 (2005); J. P. Ostriker et al., *Astrophys. J.* **722**, 642 (2010). ■