Science Frontiers in Galaxy Evolution: Deep-Wide Surveys

Henry Ferguson (STScI), Lee Armus (Caltech), Felipe Barrientos (PUC), James G. Bartlett (APC - Univ. Paris Diderot), Michael Blanton (NYU), Kirk Borne (GMU), Neil Brandt (Penn State), Carrie Bridge (Caltech), Alberto Conti (STScI), Asantha Cooray (UC Irvine), Tomas Dahlen (STScI), Mark Dickinson (NOAO), Daniel Eisenstein (U. Arizona), S. Michael Fall (STScI), Gaspar Galaz (PUC), Eric Gawiser (Rutgers), Karl Glazebrook (Swinburne), Mauro Giavalisco (UMass), Kirk Gilmore (Stanford), Fabio Governato (U. Washington), Norman Grogin (STScI), Chris Hirata (Caltech), Leopoldo Infante (PUC), Zeljko Ivezic (U. Washington), Anton Koekemoer (STScI), Jeffrey Kruk (JHU), David Larson (JHU), Kyoung-Soo Lee (Yale), Mario Livio (STScI), Jennifer Lotz (NOAO), Ray Lucas (STScI), Sangeeta Malhotra (Arizona State), Vera Margoniner (Sacramento State), Stephan McCandliss (JHU), Gerhardt Meurer (JHU), H. Warren Moos (JHU), Jeffrey Newman (U. Pittsburgh), Sami-Matias Niemi (STScI), Dara Norman (NOAO), Mirela Obric (U. Washington), Nelson Padilla (PUC), Norbert Pirzkal (STScI), Marc Postman (STScI), Roc Roskar (U. Washington), Andrew Rasmussen (Stanford), Brant Robertson (U. Chicago), Sam Schmidt (UC Davis), Ryan Scranton (UC Davis), Marc Seigar (UALR), S. Adam Stanford (LLNL), Michael Strauss (Princeton), J. Anthony Tyson (UC Davis), Ovidiu Vaduvescu (Universidad Catolica del Norte), Risa Wechsler (Stanford), David Wittman (UC Davis), Andrew Zentner (U. Pittsburgh)

Primary Contact: Henry Ferguson
Space Telescope Science Institute
3700 San Martin Drive
Baltimore, MD 21218
(410) 338-5098
ferguson@stsci.edu

This white paper outlines the need for deep, wide-area surveys of galaxies covering a broad range of redshift. The Sloan Digital Sky Survey was one of the great successes of the past decade, and has in many ways revolutionized the study of galaxy evolution, even though its primary purpose at the outset was the study of large-scale structure. We now have the technological capability to carry out much deeper imaging and spectroscopic surveys over a significant fraction of the sky. Such surveys are absolutely essential for addressing some of the central questions for understanding galaxy evolution.

The ΛCDM model has been extremely successful in explaining the large-scale structure of the universe (illustrated in Fig. 1), including temperature fluctuations in the microwave background, the large-scale clustering properties of galaxies, and density fluctuations in the intergalactic medium. There is widespread consensus that galaxies form via hierarchical gravitational collapse of over-dense regions of the universe. The smallest regions collapse first, subsequently merging to form larger galaxies or groups and clusters of galaxies. As the dark-matter halos collapse, gas within them cools and fragments to form stars. Energy released from stellar radiation, winds, supernovae, and super-massive black holes – coupled to the interstellar medium, with its evolving chemical abundances and dust content – creates a feedback cycle that counteracts the cooling of the gas and regulates the star-formation rate.

In spite of the success of the ΛCDM model and the hierarchical galaxy-formation paradigm, experts agree that our understanding of galaxy formation and evolution is incomplete. We do not understand how galaxies arrive at their present-day properties. We do not know if the various discrepancies between theory and observations represent fundamental flaws in our assumptions about dark matter or problems in our understanding of the feedback cycle. Because the process of galaxy formation is inherently stochastic, among the most important observations are those that involve large statistical samples.

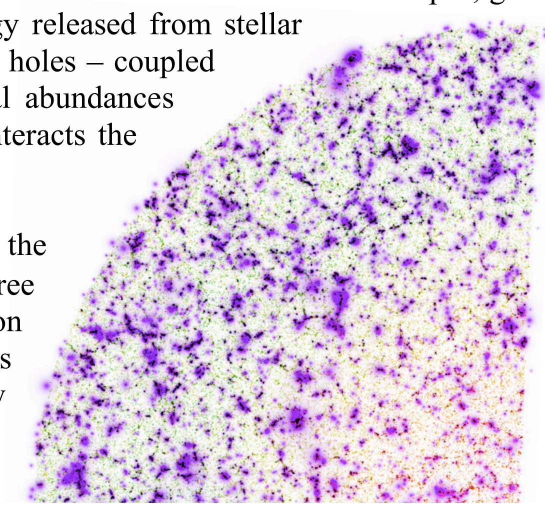


Fig. 1 Slice from a mock catalog used to model galaxies in a wide area survey, showing the galaxy distribution out to a redshift of z=0.6. In the image galaxy color is set by the observed g-r color. Blue spheres indicate the location of dark matter halos with $M>5\times10^{13}$ $M_{\odot}$. Figure credit: M. Busha & R. Wechsler (KIPAC/Stanford)

Four Questions

(1) Do we understand dark matter on galaxy scales? The most troubling discrepancies between ΛCDM-based galaxy-formation models and observations have to do with small-scale structure. Cold dark-matter halos should have a universal density profile, independent of mass.[1] This profile has a central cusp with a density that falls roughly as $\rho(r) \sim r^{-1}$ in the inner regions. Models predict that the hierarchical structure of dark-matter halos continues down to mass scales below 1 $M_{\odot}$; a Milky Way-size dark-matter halo is expected to contain ~500 halos of mass 10^7-10^8 $M_{\odot}$, which is factors of 10-100 larger than the extrapolated number of dwarf galaxies. The inner-cusp problem and the missing-satellite problem could be hinting that dark matter is either warm or self-interacting,[2] although such models have their own share of problems. Alternatively, it is possible that ejection of a large fraction of the baryons in galactic winds or angular-momentum transfer through bars can resolve the inner-cusp problem, and the missing-satellite problem can be resolved if star-formation is highly suppressed within dwarf galaxies.[3] These issues are of wide-ranging importance even if their solutions do not involve new dark-matter physics. Understanding the star-formation histories of low-mass galaxies is probably crucial to understanding the re-ionization of the intergalactic medium, as well as the chemical abundances in both the diffuse gas between galaxies and in ancient stars in the Milky Way.

(2) What regulates star formation in galaxies? Current galaxy-formation models rely on a series of standard assumptions, each of which must be subject to careful tests: that stars form where gas becomes Jeans unstable (and that the effects of magnetic fields can be ignored), that these instabilities happen in galaxy disks (i.e. most star formation occurs in disks) and in galaxy mergers, and that the initial mass function of stars is universal over most of the lives of galaxies, regardless of changes in chemistry and physical conditions. We need to test these assumptions by probing the extremes of star formation in different galaxy environments, by quantifying the changes in galaxy stellar populations over the span of cosmic time, and by confirming that the stellar mass that we see in present-day galaxies is consistent with the amount expected from our estimates of the star-formation rate over the full range of look-back times.

If galaxies form exclusively at peaks in the underlying dark-matter density field (an assumption that has not been fully tested), then there must be a fundamental relation between the luminosity function of galaxies and the mass spectrum of underlying dark-matter halos. But the luminosity function is deficient both at the bright end and at the faint end. Star formation is evidently suppressed not only in low-mass halos, but also in the most massive halos. Proposed mechanisms involve energy injection or gas ejection from supernovae; heating, photo-dissociation, and photo-ionization and photo-evaporation of gas by UV photons from early generations of stars; heating and stripping of gas in galaxy clusters; and transfer of energy from super-massive black holes into gas that would otherwise cool to form stars.[4] We do not know which processes dominate and we do not know if the feedback cycle tends to reach a smooth equilibrium or instead leads to stochastic episodes of star formation. The feedback cycle is important not only for understanding galaxies but also the intergalactic medium, which is polluted by ejected material from galaxies and heated by the energy of the feedback cycle. A significant fraction of the baryons and metals reside in the IGM, most of it presumably in a warm/hot phase, which has yet to be clearly identified or studied in any detail.

(3) How do massive black holes form and evolve within galaxies? The tightness of the relation between central black-hole mass and the stellar mass and velocity dispersion of the surrounding bulge[5] suggests that the process of forming a bulge also builds a black hole with about 0.1% of the bulge mass. Energy released from accreting black holes may be a key part of the feedback cycle that regulates star formation in massive galaxies. Nevertheless we still do not have a solid understanding of how and why black holes and bulges grow together.

Mergers and interactions of galaxies probably play a key role. Mergers of gas-rich galaxies provide fuel for star-formation, and drive gas to the center of the merger remnant, where it is needed both to form the bulge and feed the black hole.[6] Interactions create bar instabilities that can drive gas to the center even if there is no merger. There may be differences as a function of galaxy mass. The existence of luminous QSOs at z~6 indicates that the process of black-hole formation must have been very efficient in some galaxies in the early universe.[7] Understanding how black holes of masses ~ $10^9 M_\odot$ can grow within 1 Gyr remains a major challenge.

(4) How did galaxies attain their present-day shapes and sizes? High-resolution images from HST and ground-based AO have provided a great deal of information about the evolution of galaxy morphologies from the present back to within 1 Gyr of the Big Bang. The familiar spirals and ellipticals that form the backbone of the Hubble sequence emerge at redshifts between z~1 and z~2. At higher redshifts, galaxies tend to have clumpy, irregular structures, often aligned in chains. [8] The characteristic sizes of galaxies grow with time, qualitatively tracking the expected growth in the sizes of dark-matter halos. Nevertheless, despite the wealth of new data, we have only a qualitative understanding of how galaxies evolve in shape and size.

Hierarchical models of galaxy formation have been successful in explaining the morphology-density relation (the trend for early-type galaxies to occupy the highest-density regions), and explaining the tendency for the most massive galaxies to have early types. The models have been less successful in producing disk galaxies with the observed size–luminosity relation or specific angular momenta. The model galaxies tend to be too small.[9] The characteristic sizes grow by about a factor of 4 between z~1.5 and the present, even among non-star-forming galaxies. While hierarchical models predict smaller sizes at high redshifts, the observed evolution is more dramatic than the model predictions. [10]

Key Challenges for 2010-2020

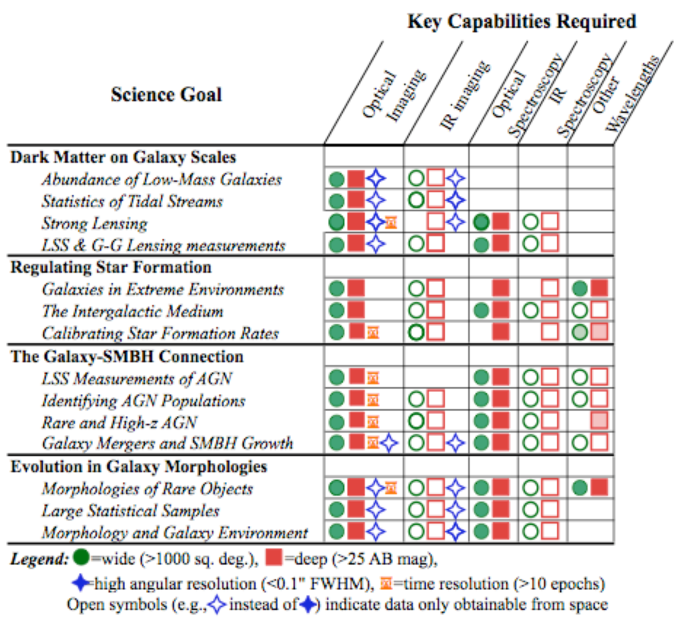
To understand galaxy evolution we will need to make significant progress on multiple fronts. Theoretical modeling must grow in sophistication, incorporating more and more realistic models of star formation and feedback. Observations must improve in sensitivity, resolution, wavelength coverage, and sky coverage. The refurbishment of HST in 2009, followed by the commissioning of JWST in 2013, will revolutionize our ability to study faint, distant galaxies in the rest-frame UV, optical and near IR. ALMA will provide high-resolution images at sub-mm wavelengths, bring powerful capabilities to probe dusty star formation, measure the molecular gas content, and constrain the dynamics of high-redshift galaxies.

An important complement to these sensitive, but narrow-field, facilities will be telescopes that can efficiently survey wide areas of the sky at sensitivities greatly exceeding our current surveys. It is within our grasp to carry out surveys that will bring about a phase transition in our ability to characterize galaxy properties and their relation to the underlying dark matter. Narrow-field facilities on their own will not achieve this because of the large volumes required to measure tagged correlation functions, find rare objects, and sample the full range of environment.

The importance of such surveys lies in the fact that galaxy formation is inherently stochastic, but that it is fundamentally governed (if our theories are correct) by the statistical properties of the underlying dark-matter density field. The halo model and the halo occupation distribution (HOD) have provided a powerful theoretical framework for quantifying the connection between galaxies and dark-matter halos. In the simplest HOD model, the multiplicity function $P(N|M)$ of subhalos within halos is given by the dark-matter model, and the details of galaxy star-formation histories map this multiplicity function to a conditional luminosity function $P(L|M)$. To the extent that it has been tested, this kind of model provides a remarkably good description of galaxy clustering.[11] Nevertheless, it is clearly only an approximation, which must break down when the details of galaxy properties are considered or the details of halos are considered.

With better observations, the HOD model approach can be generalized to encompass the full range of observed properties of galaxies. Instead of the conditional luminosity function $P(L|M)$ at a single epoch, we need to be considering multi-dimensional distributions that capture the galaxy properties we would like to explain and the halo properties that we believe are relevant: $P(L,a,b,c,\ldots \mid M,\alpha,\beta,\gamma,\ldots)$, where $a,b,c,\ldots$ are parameters such as age, star-formation rate, galaxy type, etc., and δ, β, γ, … are parameters of the dark-matter density field such as overdensity on larger scales or shape and redshift. A complete theory of galaxy formation would reproduce the mean relations in this higher-dimensional space (i.e. the fundamental scaling relations of galaxies) and their scatter. Unexplained scatter, or discrepancies in the scaling relations, signals missing physics or flaws in the model. Current surveys have only just detected the break between the one-halo and two-halo components of the correlation function.[12] We need to be able to subdivide by galaxy properties and redshift with small enough errors to quantify evolution at a level compatible with the predictive capability of the next generation of simulations.

The depth and area requirements for this level of progress are compatible with plans for JDEM and LSST or similar concepts. In the following, we consider an "LSST-like" survey to be one that covers a significant fraction of the sky (> 10^4☐°) to AB~25 over wavelengths 0.35-1μ with typical seeing ~0.7″; "JDEM-like" near-IR survey to be one that covers the same area to AB~25 with similar or better seeing; a "JDEM-like" BAO survey to be one that yields ~10^8 redshifts out to z~2; and a "JDEM-like" optical survey to be one that yields resolution of ~0.1″ over areas of >10^3☐°. All of these are important and complementary. We outline below topics that such surveys would address and attempt to highlight in Table 1 the relative importance of different capabilities for different subtopics.



(1) **Do we understand dark matter on galaxy scales?**
Progress here will involve constraining the substructure within galaxy-size dark-matter halos, and making progress in understanding star-formation in dwarf-galaxy mass halos. Goals include:

- Measuring the local space density of very low mass (and low surface-brightness) galaxies, not just around the Milky Way and its neighbors, but in representative regions of the local volume. This is a serious challenge for galaxies that have no neutral hydrogen. LSST images will be deep enough to detect typical dSph galaxies as dim as M_V=-6 within 8 Mpc, which should be distinguishable from most of the background galaxies via color, size, and surface-brightness fluctuations. We should expect >10^4 detectable satellite dSph near bright galaxies within this volume. More interesting is the density away from bright galaxies, which is entirely unknown. Follow-up observations with HST or JWST could resolve the galaxies into stars to improve the distance estimates and better constrain the star-formation histories.
- Measuring the frequency of tidal streams around galaxies, their sizes and shapes in a statistical fashion would constrain both dark-matter substructure and star-formation in low-mass halos.

While streams can be studied in resolved stars with HST or JWST, the small fields limit such studies to small samples of galaxies. An SMC stretched uniformly in a circular stream 50 kpc in radius and 1 kpc in width would have a mean surface of ~27 mag arcsec^{-2}; an LSST-like survey could identify such streams in diffuse light around galaxies within a few hundred Mpc. A wide-area survey with HST-like resolution could identify streams of much lower surface brightness via resolved stars in either the optical or near-IR out to distances of 20 Mpc, for a typical JDEM wide-area weak lensing survey, or 100 Mpc in a deep pointed survey.

- Galaxy-galaxy lenses can provide powerful constraints on halo substructure through modeling of the positions and relative brightness of the multiple images. Identification of candidates in the SDSS spectroscopic survey has proven to be extremely powerful;[13] a natural by-product of a spectroscopic survey needed for BAO measurements or a deep photometric survey needed for weak lensing measurements would be extensive lists of candidate lenses for follow-up at high resolution. Scaling the CFHTLS survey to LSST suggests 10^4 lenses in 20000 deg^2.
- On larger scales, weak lensing tomography and cross-correlations with galaxy density maps constrain the bias factor, the matter power spectrum, as well as the halo multiplicity function at $z<1$. Weak lensing on scales of r_{vir} will constrain the relation between halo masses and galaxy observables such as luminosity, color and SFR tracers. The measurement is inherently statistical and can be fully exploited only with very wide surveys. A JDEM-like redshift survey will measure the power-spectrum of galaxy clustering in the range $1<z<2$ to great precision. On large scales, it will improve on Planck measurements of the linear power spectrum. On non-linear scales, it will constrain the statistics of galaxy positions within 1 Mpc halos, and the shape of the power-spectrum in the quasi-linear regime to high precision.

(2) What regulates star formation in galaxies?

- To understand what regulates star formation in galaxies we need to study galaxies across a wide range of epochs and a wide span of density. LSST- and JDEM-like surveys encompass volumes ranging from ~10 to 10^3 Gpc^3 within z<6. Weak-lensing tomography, deep photometric redshift surveys including the near-IR, and wide-area spectroscopic surveys encompassing large volumes are critical for identifying overdensities and characterizing the galaxy properties within them. At low redshifts, such surveys will complement studies of hot gas from the Sunyaev-Zeldovich effect or x-ray surveys, while at $z>1.5$ deep-wide surveys that include the NIR will be the most efficient way to identify clusters and groups and quantify their densities. Identifying extreme underdensities (voids) is difficult with photometric redshifts but a natural product of BAO spectroscopic surveys.
- Studies of the intergalactic medium can shed light on galaxy formation and the feedback cycle. HST/COS should be a tremendous step forward, and future UV or x-ray missions could probe the warm/hot medium in detail. A complementary approach is provided by cross-correlation of a wide-area redshift survey with the CMB. Cross-correlation of galaxy density maps with thermal SZ maps measure the galaxy gas-pressure cross-correlation (constraining the energy input as a function of redshift). Cross-correlation with kinetic SZ maps (possible only with a redshift survey) measures the galaxy–electron cross-correlation. Measurements of the radial electron-density profile around a typical galaxy will characterize the distribution and evolution of the missing baryons – a key test of galaxy evolution models.
- It is essential to have multiple methods to estimate star-formation rates, metallicities, nuclear activity, dust contents, and stellar masses for large samples of galaxies. Colors and luminosities from optical (rest-UV) surveys provide one estimator of star-formation rates and extinctions. NIR imaging will greatly improve not only the photometric redshift estimates but

also stellar-mass estimates via the longer wavelength baseline. Such imaging could be a natural by-product of a JDEM-like BAO survey. The Hα line-strengths and equivalent widths from a BAO survey would complement broad-band star-formation rate estimates. Hα provides a different lever on dust and IMF, and comparisons of Hα and rest-frame UV measurements can constrain the IMF and stochasticity of star formation.[14] A BAO survey would also measure metal lines such as [OII] and [OIII] in hundreds of thousands of galaxies. Supernova rates from future deep-wide surveys will provide yet another measurement of star-formation rate (and perhaps IMF and metallicity with future calibrations).

(3) How do massive black holes form and evolve within galaxies?

- The relationship between AGN and dark matter halos, their environments, and the duty cycles of AGN activity, can be constrained via observations of their space density and large-scale clustering. Any scatter increases the contribution from lower-mass (and less highly biased) halos so that a measurement of large clustering amplitude limits the contribution from lower mass objects. This requires large samples of AGN spanning a wide range of redshift, luminosity, and environment. QSO-galaxy cross-correlations will establish the halo mass of QSOs and explore the environmental dependence of AGN activity.
- The evolution of the AGN luminosity function (LF) reflects an evolution in black hole masses as well as an evolution in gas supply and the lifetimes of active phases.[15] Trends with redshift both above and below the LF break, which deep-wide surveys will probe with overwhelming statistics, will provide important discrimination between models. LSST should yield 20-80 million AGN, with about 1000 at z = 6.5-7.5 identifiable via the Lyman break. This could be pushed to z>12 if JDEM provides wide area near-IR images. A JDEM BAO redshift survey could identify AGN via broad lines, with roughly 2 million expected. Spectroscopy will enable small-scale clustering studies not possible with photometric redshifts, as well as probe the evolution of metal lines such as CIV at redshifts z<12.
- It is likely that AGN spend most of their lives in low-luminosity phases, which are dimmer than their host galaxies, but probably varying. These will be revealed with great statistical accuracy by projects such as LSST, including objects where, e.g., X-rays are heavily obscured on very small scales, but where the optical/UV is not so heavily obscured. There are clear examples of such objects, such as BAL Quasars. The systematic evolution of variability is virtually unexplored, and would provide a new window into accretion physics.
- Very luminous objects (useful for follow-up spectroscopy) are rare enough that narrow-field surveys generally will not find them. Deep-wide surveys are required to find targets for JWST and ALMA, as well as 30-m class telescopes and IXO. Follow-up by ALMA can in principle constrain the kinematics of the underlying galaxy from molecular lines.
- Studies of galaxy pairs and mergers are essential if we are to understand the triggering mechanisms for star-formation (which forms the bulges) and nuclear activity. Large-area surveys will allow us to quantify the incidence of binary AGN and the correlation of AGN activity with mergers of various types (e.g. mass ratios, ages and star-formation rates). Sensitive NIR host studies will allow one to push beyond z ~ 1.5, to see how SMBH/host-galaxy relations evolve for the first third of cosmic time.

(4) How did galaxies attain their present-day shapes and sizes?

- Models are reaching the stage where they can begin to predict the shapes of galaxies, star-formation rates, dust distribution, and AGN activity through the ~10^8yr merger process. A decade from now models will have progressed to the point where they can produce large catalogs of simulated mergers with various mass ratios, spins, orbits, and gas and dust contents, as well as tidal interactions spanning a large range of parameters. Deep-wide surveys are the only way to build up adequate samples to put these models to statistical test.

- High-resolution imaging has so far provided a rough sketch of the evolution of normal galaxy sizes and morphology. Sample sizes must grow by several orders of magnitude before we will have the statistics to address quantitatively such questions as whether star-formation at high redshifts occurs primarily in disks, how fast disks and bulges grow and whether they grow from the inside out, whether bar and bulge statistics as a function of redshift are consistent with secular bulge growth, whether disk thickness is a function of time or environment, or whether the incidence of close pairs and disturbed morphologies in non-star-forming galaxies is consistent with the dry-merging hypothesis for increasing their sizes.
- A JDEM-like BAO spectroscopic survey would be an ideal complement to high-quality imaging. With only photometric redshifts, in spite of large samples, projection effects will suppress the statistical correlations between galaxy morphology and local environment.

The key questions in galaxy evolution over cosmic time require deep, wide-area surveys to complement the more directed studies from HST, JWST and ALMA and other narrow-field facilities. The essential correlation of galaxy properties with dark matter – both on small scales in the local universe and in gravitational lenses, and on the Gpc scales required for large-scale structure – requires a new generation of wide-area surveys. Fortunately, such surveys are also essential for constraining the nature of Dark Energy, hence there is a great deal of commonality in the techniques we need to address the deepest questions of cosmology and galaxy evolution.

---

[1] Navarro, Frenk & White; Moore; Springel; Dubinski & Carlberg 1991, ApJ, 378, 496
[2] Colin et al. 2000, ApJ, 542, 622; Bode, Ostriker, and Turok, 2001, ApJ, 556, 93; Spergel & Steinhardt 2000, PRL, 84, 3760, Kaplinghat et al. 2000, PRL, 85, 3335; Davé et al. 2001, ApJ, 547, 574
[3] Babul & Rees 1992, MNRAS, 255, 346; Efstathiou 1992, MNRAS, 256, 43, Thoul & Weinberg 1996, ApJ, 465, 608, Bullock et al. 2000, ApJ, 539, 517; Robertson et al. 2005, ApJ, 632, 872; Weinberg & Katz 2000.
[4] Bower et al. 2006, MNRAS, 370, 645; Benson et al. 2000, MNRAS, 311, 793; Croton et al. 2006, MNRAS, 365, 11; Dekel & Silk 1986, ApJ, 303, 39; Kauffmann & Haehnelt 2000, MNRAS, 311, 576; Murray et al 2005, ApJ, 618 569; Robertson & Kravtsov 2008, ApJ, 680, 1083; Somerville et al. 2001, MNRAS, 320, 504; Springel et al. 2005, MNRAS, 361, 776; Springel et al. 2005, Nature, 435, 629; Wyithe & Loeb 2003, ApJ, 595, 614
[5] Kormendy & Richstone 1995; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Magorrian et al. 1998, AJ, 115, 2285; Marconi & Hunt 2003, ApJ, 589, 21; Haring & Rix 2004, ApJ, 604, 89
[6] Barnes & Hernquist 1992, ARA&A, 30, 705; Mihos & Hernquist 1994, ApJ, 431, 9; Di Matteo et al. 2005, Nature, 433, 604; Soifer et al. 1984, ApJ, 278, 71; Sanders & Mirabel 1996, ARAA, 34, 749
[7] Fan et al. 2000, AJ, 120 , 1167; Fan et al. 2006, AJ, 131, 1203; Efstathiou & Rees 1988, MNRAS, 320, 5
[8] Cowie et al. AJ, 110, 1576; Elmegreen et al. 2005, ApJ, 631, 85
[9] Navarro & Steinmetz 2000, ApJ, 538, 488; Abadi et al. 2003, ApJ, 591, 499; Sommer-Larsen et al. 2003, ApJ, 596, 47; Governato et al. 2007, MNRAS, 374, 1479; Robertson et al. 2004, ApJ, 606, 32
[10] Ferguson et al. 2004; Daddi et al. 2005; Trujillo et al. 2006; van der Wel et al. 2008; Robertson et al. 2006, ApJ, 641, 21; Khochfar & Silk 2006, MNRAS, 370, 902; van Dokkum et al. 2008, ApJ, 677, 5
[11] Berlind et al. 2002, ApJ, 575, 587; Cooray 2006, MNRAS, 365, 842, VandenBosch et al. 2003, MNRAS, 340, 771; Zheng et al 2005, ApJ, 633, 791; Tinker et al. 2006, ApJ, 647, 737; Berlind et al. 2005, ApJ, 629, 625
[12] Zehavi et al., 2004, ApJ, 608, 16; Blake et al. 2008, MNRAS, 385, 1257; Zheng et al. 2007, ApJ, 667, 760; Lee et al., 2006, ApJ, 642, 63; Ouchi et al., 2005, ApJ, 635, 117
[13] Bolton, A., et al. 2006, ApJ, 638, 703
[14] Meurer et al. 2009, ApJ, in press
[15] Hopkins et al. 2006