

THE STRUCTURE AND KINEMATICS OF GALAXIES¹

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A major thrust of astrophysical research in the coming decade will focus on the structure and kinematics of galaxies, both locally and at high redshift. We discuss several representative science questions in this field that are expected to drive the design, development and implementation of new observing facilities: i.e., the structure of dark matter halos on galaxy scales, the push toward a set of universal galaxy scaling relations, the origin of galactic nuclei, and 2D mapping of the history of cosmic star formation and chemical enrichment within individual galaxies. Our recommendations for the next generation of telescopes and instruments needed to make headway in these areas include facilities that are nearing commissioning (JWST and ALMA) or are in mature stages of development (TMT or an equivalent 30m-class optical telescope). For new initiatives, our highest recommendation is for a wide-field (FOV $\sim 0.5\text{--}1\text{ deg}^2$), optical/IR imaging space telescope with HST-like resolution; such a facility would enable transformational science and ensure a leadership role for Canadian astronomy in this field for the foreseeable future. The Canadian community should also explore options for participation in a project to implement an 8m-class telescope with a wide-field, highly multiplexed optical/IR spectrograph (i.e., a WFMOs-like instrument). On still longer timescales, a significant impact in this field can be expected from both the Square Kilometer Array (SKA) and International X-ray Observatory (IXO).

1. INTRODUCTION

The structure and kinematics of galaxies is a well established field in astrophysics. As such, it has featured prominently in many past attempts to identify the key science questions driving the design and development of new observing facilities (e.g., Pudritz et al. 2000). Indeed, the telescopes and instruments currently available to Canadian astronomers were motivated in large part by fundamental questions in galaxy structure and kinematics. This is unlikely to change in the coming decade, as our understanding of structure formation on spatial scales of \sim tens of pc to $\lesssim 1$ Mpc inevitably rests on observations and modeling of *galaxies*. This is also a field in which Canadian astronomers have historically played a leading role, and the recommendations below, while ambitious, are intended to keep the Canadian community at the forefront of this rapidly evolving field.

Because this is an extraordinarily broad topic, we restrict the discussion to a handful of the most pressing questions in the general area of galaxy structure and kinematics. Although this list is necessarily incomplete, these topics are representative of those that are expected to drive the next generation of research facilities. Other White Papers discuss specifically issues related to nearby (i.e., Local Group) galaxies, galaxy formation, and galaxy evolution and clustering, so we shall focus here on the low-redshift ($0 \lesssim z \lesssim 0.5$) universe, paying particular attention to galaxies beyond the Local Group and out to the Virgo and Fornax Clusters (≈ 20 Mpc).

1.1. Case #1: The Structure of Dark Matter Halos

Dark matter is the dominant form of matter in the universe, yet its nature remains unknown. Its importance in governing the internal structure and kinematics of individual galaxies can scarcely be overestimated: as the growth of galaxies proceeds hierarchically, baryons cool and condense within collapsing and merging halos whose gravitational potential is dominated by dark matter (Fig. 1). Simulating the detailed structure of galaxies formed in this way, beginning with cosmologically moti-

vated initial conditions, has been an area of intense activity during the past decade (e.g., Springel et al. 2005; Navarro et al. 2010). While these simulations show excellent agreement with observations on large scales, there are significant discrepancies on the scales of galaxies themselves: e.g., the central density structure of the dark matter halos is poorly known for most galaxies, and the largest galaxies are predicted to contain far more “subhalos” than are identified in searches for satellite galaxies (see, e.g., the discussion in Ludlow et al. 2009).

Reconciling, *in detail*, the observed and predicted structure of dark matter halos is a critical open question that will remain a high-priority for both observers and modelers alike in the years ahead. Key questions will include the level of triaxiality in the dark matter halos, and the central and global density structure of the dark matter on mass scales ranging from galaxy clusters ($\sim 10^{14\text{--}15} M_\odot$) down to ultra-faint dwarf spheroidal galaxies ($\lesssim 10^7 M_\odot$), which has implications for both the nature of dark matter itself and for its detection via γ -ray emission from self-annihilation (e.g., Taylor & Silk 2003). Furthermore, a major thrust in the decade ahead will be the characterization, through both observations and models, of individual dark matter substructures: at present, their effect on the final distribution and kinematics of the baryons within galaxies is likely underestimated, as they may regulate the formation and evolution of spiral waves, bars, warps, and bulges (and thus drive the overall galaxy morphology).

1.1.1. Facility Requirements

Such efforts will require observations and modeling using a variety of techniques (see Fig. 2), including weak and strong lensing, 2D integrated-light spectroscopy, radial velocity measurements of kinematic tracers, and/or X-ray observations. Integrated-light, 2D spectroscopy for $z \lesssim 1$ galaxies showing strong lensing features will require IFUs on 8m/30m-class facilities; with sufficient spectral resolution ($R \approx 5000$), these same facilities will allow observations similar to those performed with WHT/SAURON (Emsellem et al. 2007) to be extended into the “dwarf” galaxy regime locally. IFU spectroscopy for thousands of galaxies at intermediate redshifts would

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also allow mass modeling from stellar dynamics and weak lensing, using stacked samples. For more nearby systems, IFU spectroscopy of galaxy cores could be combined with radial velocity measurements for thousands of dynamical tracers — such as globular clusters, planetary nebulae and satellite galaxies (Woodley et al. 2007) — as well as wide-field, high-sensitivity X-ray profiles (available in the post 2020 era from *IXO*) for the hot gas surrounding individual galaxies to greatly improve on existing mass profile measurements. On these timescales, the SKA will also have a profound impact in this field, allowing routine measurement of rotation curves for galaxies out to $z \sim 0.5$ and discovering tens of thousands of strongly lensed galaxies. However, the highest priorities in this area — on intermediate timescales — are a 30m-class optical/IR telescope, a WFMOS-like instrument on an 8m-class telescope and a *wide-field imager*, operating in the optical/IR, with a stable PSF and angular resolution approaching HST.

1.2. Case #2: Unification of Galaxy Scaling Relations

The scaling relations of galaxies (e.g., the Tully-Fisher and Faber-Jackson relations, Fundamental Plane, etc) continue to yield some of the most powerful constraints available on the physical processes that governed their formation and evolution (e.g., Navarro & Steinmetz 2000; MacArthur et al. 2003; Dutton et al. 2007; Courteau et al. 2007ab). During the past decade, significant progress has been made in understanding the complex history of mergers and accretions, gas inflows, radiative cooling, star formation, and feedback that gave rise to the scaling relations observed for galaxies in the low- z universe.

Until recently, this field has tended to focus on the highest-mass galaxies (due to the technical challenges in obtaining accurate photometric and kinematic data for low-mass, low-surface brightness systems), viewing them as isolated, virialized systems that fall into two distinct categories: i.e., rotationally-supported spirals and dynamically “hot” ellipticals. The interrelationships between these systems — and the extension to the regime of dwarf galaxies ($\lesssim 10^{10} M_{\odot}$) that dominate galaxy populations in terms of overall numbers — remain largely unexplored, although there are surprising indications from many recent studies for commonalities in the photometric and structural scaling relations spanning factors of thousands or more in baryonic mass (e.g., Gavazzi et al. 2005; Ferrarese et al. 2006a; Zaritsky et al. 2006; Wolf et al. 2009; see also Fig. 3).

For galaxies at the high-mass end of the “red sequence”, IFU spectroscopy for a large sample of nearby, early-type galaxies has called into question the assumption of a fundamental distinction between E and S0 morphological types (e.g., Emsellem et al. 2007; Fig. 4), while there is mounting evidence (e.g., Kassin et al. 2007) for a possible physical connection between the Tully-Fisher relation of “spirals” and the Fundamental Plane of “ellipticals”. A key challenge for the decade ahead will lie in determining the extent to which a “unified” set of scaling relations can describe the properties of galaxies of differing morphological type and spanning the full range in mass.

1.2.1. Facility Requirements

Progress in this field will necessarily hinge on homogeneous photometric and spectroscopic data for complete and unbiased galaxy samples, preferably selected using objective criteria such as stellar mass or location in the galaxy color-magnitude relations (e.g., Balogh et al. 2004). LSST can be expected to have a revolutionary impact in this field, covering half the sky in six optical/IR bands to a depth of $r \approx 27.5$. The limited angular resolution ($\approx 0''.5$ – $1''.0$) of the survey, however, will pose a problem for small-scale features in the nearest and most distant galaxies (see below); a wide-field IR imaging survey at higher angular resolution, such as being planned for JDEM and Euclid (or from a pointed mission), will far exceed what is possible with LSST. Spectroscopy of galaxies identified in wide-field imaging surveys of this sort must come from a variety of facilities, operating at optical/IR and/or mm/radio wavelengths, to measure the kinematics of both stars and gas. More locally, wide-field imaging at optical/IR wavelengths can be combined with 2D spectra from 8m- and 30m-class telescopes to establish the low-mass end of the scaling relations at $z \approx 0$.

1.3. Case #3: Galactic Nuclei: The Role of Feedback and the Connection to Supermassive Black Holes

High-resolution imaging of galaxy centers with HST has provided important insights into their formation, evolution and relation to overall galactic structure. A picture emerged in the late 1990s in which the oldest and highest-mass galaxies (i.e., masses $\gtrsim 10^{10} M_{\odot}$) could be neatly divided into two types based on the logarithmic slope of the central luminosity profiles: the so-called “core” and “power-law” galaxies (e.g., Faber et al. 1997). The working hypothesis at that time was that these differences in central structure arose as a result of supermassive black hole (SBH) binary evolution in the most massive systems, which flattened the initially steep density profiles of the progenitor (=pre-merger) galaxies.

While this basic picture remains essentially correct, wider-field HST imaging for an expanded samples of galaxies — and including the low-mass galaxies that were largely absent from earlier surveys — has shown the central structure of galaxies to vary in a much more systematic (and unexpected) way (see Fig. 5). As galaxy mass decreases, so too does the central surface brightness, transitioning from a luminosity *deficit* relative to a global model, to a luminosity *excess*. Ultimately, the galaxy takes on a two-component structure, in which a compact, structurally-distinct “nucleus” or “nuclear star cluster” is superimposed on an underlying galaxy component (Côté et al. 2007). The origin of these nuclei remains an open question, although preliminary evidence suggests that gas inflows followed by star formation and stellar (and/or AGN) feedback is likely to play an important role. Because AGN feedback plays an absolutely fundamental role in our current understanding of galaxy formation (e.g., Croton et al. 2006), understanding the internal structure, star formation histories, and metallicities of these nuclei is certain to be a high priority in the coming decade. This is particularly true since the mass-fraction of these nuclei in the low- and intermediate-mass galaxies, and across a range of Hubble Types (Seth et al. 2008; Fig. 5), is remarkably similar to that of the SBHs in the highest-mass galaxies, suggestive of a possible connection between these two types of central mass concen-

tration (Ferrarese et al. 2006b; Wehner & Harris 2006).

1.3.1. Facility Requirements

As the lower panel of Fig. 5 shows, high angular resolution is an essential pre-requisite for the study of compact sources in the centers of galaxies. (This is equally true of either nuclei or SBHs.) Observations with ALMA of molecular gas in the cores of nearby galaxies will provide an exciting new constraint of the small-scale mass distributions in these galaxies. Both JWST and a diffraction-limited IFU on a 30m-class optical/IR telescope will have a profound impact in this field by measuring the star formation and chemical enrichment histories of the nuclei and underlying galaxies directly, via integrated-light spectroscopy and, in some cases, through CMD-modeling of the resolved stellar populations. Serious limitations for both facilities, however, are their small fields of view, meaning that they will be used only to carry out pointed observations for a small subset of potential targets. An unbiased census of the incidence of nucleation across the Hubble Sequence, along the galaxy mass function, and as a function of environment, will require a wide-field, high-resolution optical/IR survey: i.e., resolution comparable to HST but with a $\sim 100\times$ increase in FOV.

1.4. Case #4: Resolving the Cosmic History of Star Formation and Chemical Enrichment

The past decade has witnessed an explosion of interest in the field of “near field cosmology”, in which the resolved stellar populations are used to reconstruct the detailed history of star formation and chemical enrichment within individual galaxies (e.g., Fig. 6). These efforts have shown conclusively that low- and intermediate-mass galaxies exhibit a bewildering diversity in their evolutionary histories (e.g., Grebel 2000; Shetrone et al. 2001, Venn et al. 2004) and that the “classical” view of luminous galaxies like M31 as simple bulge+disk+halo systems are extreme oversimplifications (e.g., Ibata et al. 2001; McConnachie et al. 2009). At the same time, pointed observations across the electromagnetic spectrum of an ever-increasing number of deep fields (e.g. GOODS, GEMS, COSMOS, AEGIS) have been used to trace out the history of star formation and chemical enrichment within large ensembles of galaxies.

Connecting these two independent windows into the evolution of galaxies over cosmic time will be a major focus of research in the coming decade. The exceptional angular resolution of HST has played an absolutely pivotal role in allowing researchers to study the internal properties (global morphologies, bar fractions, bulge-to-disk ratios, etc) of distant galaxies — and their variation with redshift — in a systematic way (e.g., McGee et al. 2008, Peng et al. 2009), although extant surveys cover exceedingly small fields (i.e., even the widest of the HST deep surveys, COSMOS, spans just 2 deg^2). At low redshift, the primary objective in the coming decade will be to push the study of resolved stellar populations out to greater volumes, and especially to $D \sim 20$ Mpc, where the vast galaxy populations of the Virgo and Fornax Clusters come within reach.

1.4.1. Facility Requirements

Pioneering efforts with HST have demonstrated the feasibility of probing the upper RGB in galaxies in the

range 10-17 Mpc (Harris et al. 2007; Williams et al. 2007; Fig. 6). Although it is possible with HST/ACS to reach a depth in Virgo equivalent to that attained in the ongoing CFHT/MegaCam survey of M31 (McConnachie et al. 2009), complete areal coverage for galaxies in this distance range is impractical because of the small HST FOV. While pointed observations with JWST, or an imaging IFU on a 30m-class telescope, will reach depths much greater than anything that has yet been achieved with HST, the real advance in this field would come from a wide-field space imager operating in the UV/optical/IR spectral region (see Fig. 7). In realistic time allocations, such a facility could obtain CMDs for hundreds, or thousands, of galaxies comparable in depth and precision to what is currently available for M31. Deep, pointed exposures with such a facility would also be the natural step forward from the current, state-of-the-art HST surveys (e.g., COSMOS), allowing follow-up with JWST, TMT, and ALMA of carefully chosen subsets of sources.

2. SUMMARY AND RECOMMENDATIONS

Facilities: Table 1 summarizes the facility requirements described above, including, for each topic, a (subjective!) measure of the possible impact in that particular sub-field. Our primary conclusion is that significant advances are expected from ALMA, JWST and especially TMT (or an equivalent 30m-class optical/IR telescope). On longer (i.e., post 2020) timescales, we anticipate substantial new insights from SKA and IXO. Our two highest recommendations, on intermediate timescales, are for two new initiatives. First and foremost, Canadian researchers should take the lead in establishing a wide-field, high-resolution, space-based imaging capability. Such a facility would enable transformational science in galaxy formation, structure and evolution, and would ensure a leadership role for Canadian astronomy in this field for the foreseeable future. At the same time, the community should explore the options for implementing an 8m-class telescope with a wide-field, highly multiplexed optical/IR spectrograph (i.e., a WFMOs-like instrument).

Computing: The interpretation of increasingly complex and extensive datasets will continue to rely heavily on codes that simulate the formation of galaxies through hierarchical collapse and subsequent dynamical evolution. Producing realistic galaxy models will require both algorithmic improvement and advances in the spatial and temporal dynamic range needed to follow some processes with the necessary number of particles or grid elements. To attain the necessary supercomputing power, cutting-edge parallel clusters (e.g., SHARCNET, SCINET, Westgrid, etc) will need to be maintained and expanded to $\sim 100K$ cores while existing codes can be modified to take advantage of the dramatic increases in speed made possible by the introduction of graphic processing units.

Personnel: In the era of increasingly ambitious and collaborative observing programs, it is clear that investments in personnel — rather than facilities alone — will be essential if Canada is to continue in a leadership role in this, or any other other, field. Forefront research requires dedicated teams of highly qualified individuals, specifically, *postdoctoral fellows*, who will assume leadership roles in programs that address the key scientific questions of the day.

REFERENCES

- Balogh, M. L., Baldry, I. K., Nichol, R., Miller, C., Bower, R., & Glazebrook, K. 2004, *ApJ*, 615, L101
- Côté, P., et al. 2007, *ApJ*, 671, 1456
- Côté, P., et al. 2009, Report of the CSA Discipline Working Group on Wide-Field Imaging from Space, <http://orca.phys.uvic.ca/~pcote/final.pdf>
- Courteau, S., McDonald, M., Widrow, L. M., & Holtzman, J. 2007a, *ApJ*, 655, L21
- Courteau, S., Dutton, A. A., van den Bosch, F. C., MacArthur, L. A., Dekel, A., McIntosh, D. H., & Dale, D. A. 2007b, *ApJ*, 671, 203
- Croton, D. J., et al. 2006, *MNRAS*, 365, 11
- Dutton, A. A., van den Bosch, F. C., Dekel, A., & Courteau, S. 2007, *ApJ*, 654, 27
- Emsellem, E., et al. 2007, *MNRAS*, 379, 401
- Ferrarese, L., et al. 2006a, *ApJS*, 164, 334
- Ferrarese, L., et al. 2006b, *ApJ*, 644, L21
- Gavazzi, G., Donati, A., Cucciati, O., Sabatini, S., Boselli, A., Davies, J., & Zibetti, S. 2005, *A&A*, 430, 411
- Grebel, E. K. 2000, *Star Formation from the Small to the Large Scale*, 445, 87
- Harris, W. E., Harris, G. L. H., Layden, A. C., & Wehner, E. M. H. 2007, *ApJ*, 666, 903
- Ibata, R., Irwin, M., Lewis, G., Ferguson, A. M. N., & Tanvir, N. 2001, *Nature*, 412, 49
- Ludlow, A. D., Navarro, J. F., Springel, V., Jenkins, A., Frenk, C. S., & Helmi, A. 2009, *ApJ*, 692, 931
- Kravtsov, A. 2010, *Advances in Astronomy*, 2010, 8
- MacArthur, L. A., Courteau, S., & Holtzman, J. A. 2003, *ApJ*, 582, 689
- McConnachie, A. W., et al. 2009, *Nature*, 461, 66
- McGee, S. L., Balogh, M. L., Henderson, R. D. E., Wilman, D. J., Bower, R. G., Mulchaey, J. S., & Oemler, A., Jr. 2008, *MNRAS*, 387, 1605
- Mihos, J. C., Harding, P., Feldmeier, J., & Morrison, H. 2005, *ApJ*, 631, L41
- Napolitano, N. R., et al. 2009, *MNRAS*, 393, 329
- Navarro, J. F., & Steinmetz, M. 2000, *ApJ*, 538, 477
- Navarro, J. F., et al. 2010, *MNRAS*, 402, 21
- Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2009, *arXiv:0912.0731*
- Pudritz, R., et al. 2000, *The Origins of Structure in the Universe*, <http://www.casca.ca/lrp/front-back/en-index.html>
- Sand, D. J., Treu, T., Smith, G. P., & Ellis, R. S. 2004, *ApJ*, 604, 88
- Seth, A., Agüeros, M., Lee, D., & Basu-Zych, A. 2008, *ApJ*, 678, 116
- Shetrone, M. D., Côté, P., & Sargent, W. L. W. 2001, *ApJ*, 548, 592
- Springel, V., et al. 2005, *Nature*, 435, 629
- Taylor, J. E., & Silk, J. 2003, *MNRAS*, 339, 505
- Venn, K. A., Irwin, M., Shetrone, M. D., Tout, C. A., Hill, V., & Tolstoy, E. 2004, *AJ*, 128, 1177
- Wehner, E. H., & Harris, W. E. 2006, *ApJ*, 644, L17
- Williams, B. F., et al. 2007, *ApJ*, 654, 835
- Wolf, J., Martinez, G. D., Bullock, J. S., Kaplinghat, M., Geha, M., Munoz, R. R., Simon, J. D., & Avedo, F. F. 2009, *arXiv:0908.2995*
- Woodley, K. A., Harris, W. E., Beasley, M. A., Peng, E. W., Bridges, T. J., Forbes, D. A., & Harris, G. L. H. 2007, *AJ*, 134, 494
- Zaritsky, D., Gonzalez, A. H., & Zabludoff, A. I. 2006, *ApJ*, 638, 725

Table 1: Telescope and Instrument Matrix

Facility or Instrument	Time Frame	Case #1	Case #2	Case #3	Case #4
Wide-Field Space-based Imager ($0.2\text{--}2.5\mu\text{m}$), $\theta \sim 0.1''$, $\text{FOV} \gtrsim 0.5 \text{ deg}^2$	~2018	1	1	1	1
30m/WFOS ($0.33\text{--}1\mu\text{m}$), $\mathcal{R} \sim 5 \times 10^3$, $\text{FOV} \sim 10^2 \text{ arcmin}^2$	2018	1	2	3	1
8m/WFMOS ($0.4\text{--}1\mu\text{m}$), $\mathcal{R} \gtrsim 10^4$, $\text{FOV} \sim 1\text{--}2 \text{ deg}^2$	2017:	1	2	3	1
30m/IRIS ($0.8\text{--}2.5\mu\text{m}$), $\theta_{DL} \sim 10\text{--}20 \text{ mas}$, $\text{FOV} \lesssim 2 \text{ arcsec}^2$	2018	3	3	1	1
JWST/NIRSpec ($1\text{--}5\mu\text{m}$), $\mathcal{R} \sim 1 \times 10^3$, $\theta \sim 0''.08$	2014	...	2	1	2
LSST ($0.33\text{--}1.1\mu\text{m}$), $\text{FOV} \sim 10 \text{ deg}^2$	~2020	2	1	3	2
ALMA, $30\text{--}120 \text{ GHz}$, $\theta \sim 0.1''$	2013	...	2	1	3
8m/IFU ($0.33\text{--}1\mu\text{m}$), $\mathcal{R} \sim 5 \times 10^3$, $\text{FOV} \gtrsim 0.2 \text{ deg}^2$	2012	3	1	2	...
SKA, $0.06\text{--}35 \text{ GHz}$, $\text{FOV} \sim 1 \text{ deg}^2$	>2020	1	1	2	2
IXO, $\Delta E = 0.3\text{--}7 \text{ keV}$, $\theta \sim 5''$, $\text{FOV} \sim 0.2 \text{ deg}^2$	>2020	1	3	2	3

Priority Index: 1 (highest), 3(lowest)

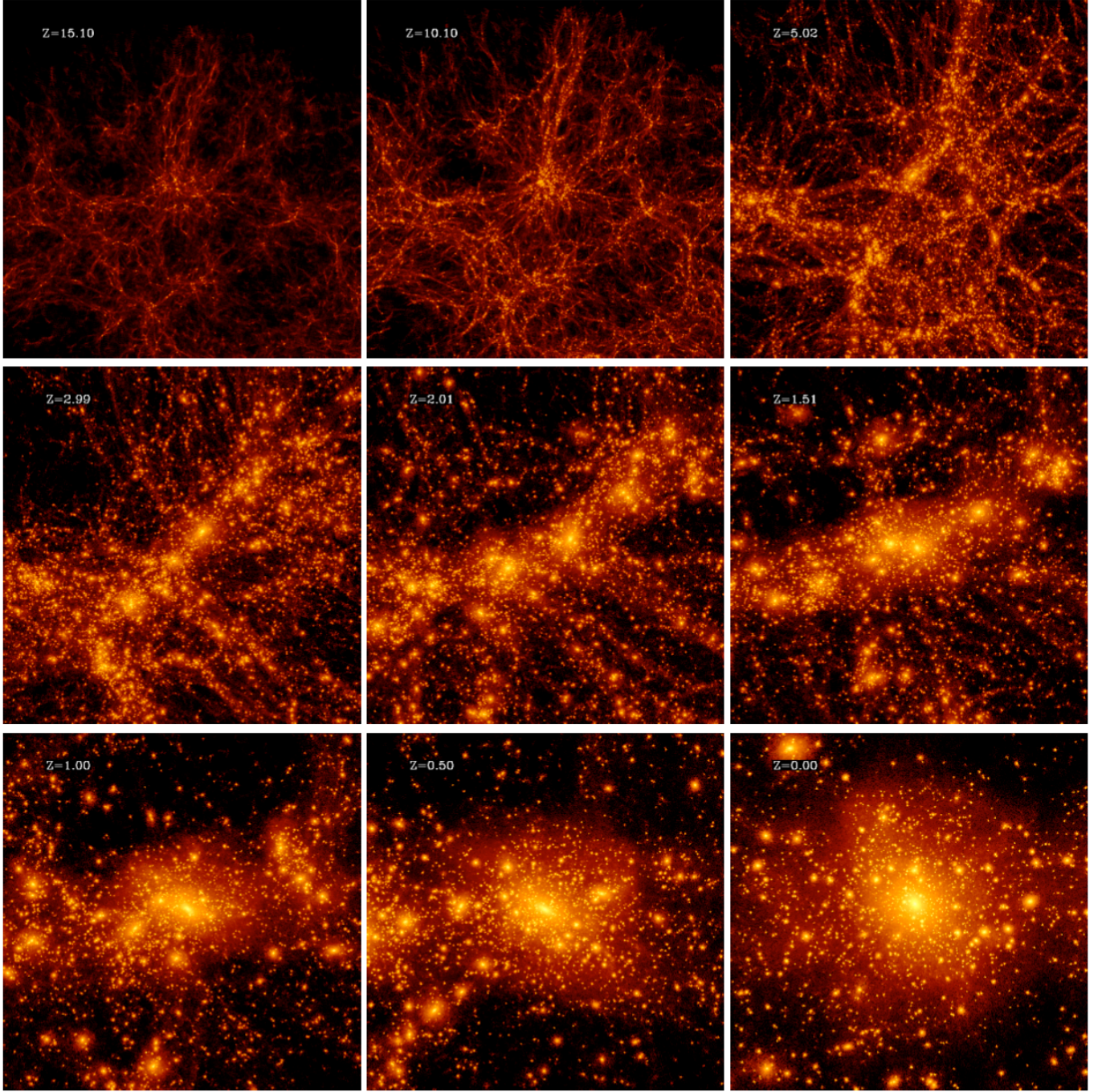


FIG. 1.— Nine stages in the formation of a Milky Way-sized dark matter halo in a Λ CDM cosmological simulation. The dark matter density is shown using a logarithmic stretch, with the scale changing from ≈ 3 comoving Mpc at $z = 15$ to ≈ 1 comoving Mpc at $z = 0$. The growth of the galaxy proceeds through a series of major and minor mergers, with significant dark matter substructure remaining at $z = 0$. Figure from Kravtsov (2010). Understanding the detailed structure of dark matter halos will remain a high-priority for both observers and modelers alike in the years ahead.

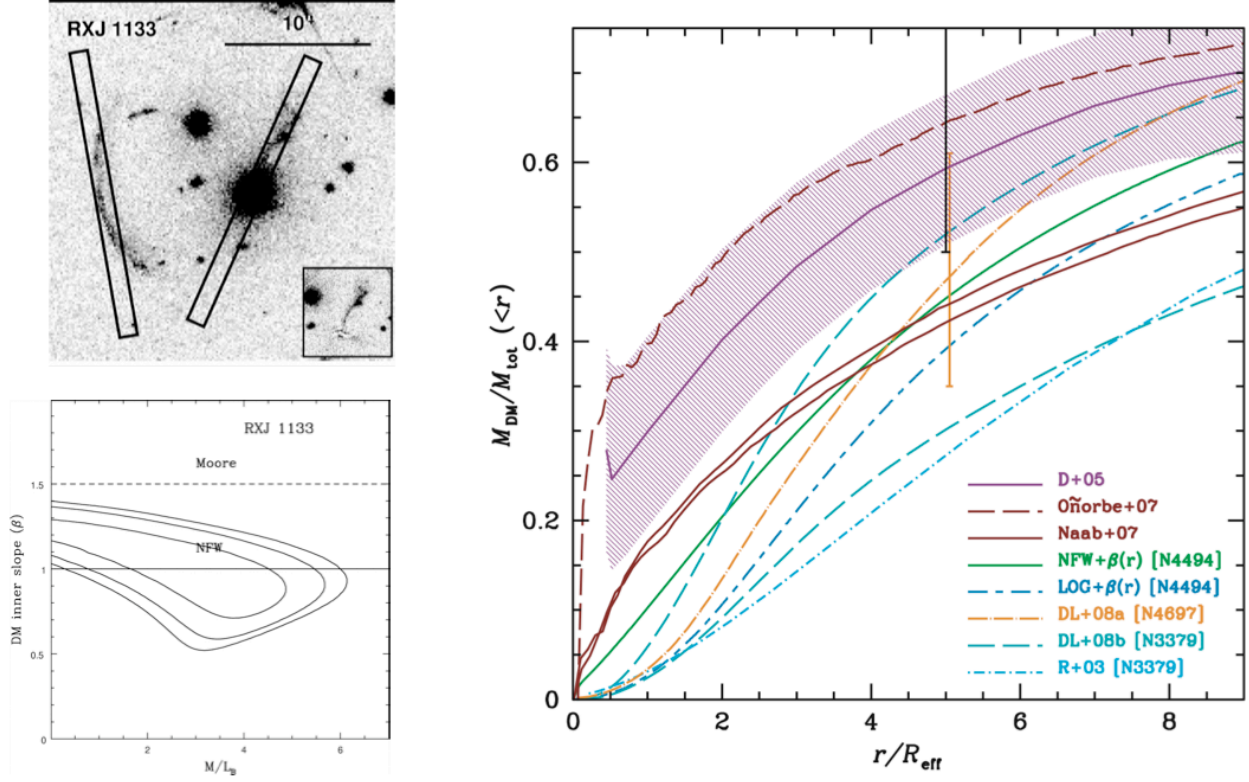


FIG. 2.— (*Upper Left Panel*) HST image for the brightest cluster galaxy in the cluster RX J1133 ($z \approx 0.39$) which shows both radial and tangential arcs. The rectangular regions show the Keck/ESI slit orientations used to obtain integrated-light spectroscopy of the central galaxy and arcs. (*Lower Left Panel*) Likelihood contours (68%, 95%, and 99%) on the inner dark matter slope and galaxy mass-to-light ratio for the above system. Figure from Sand et al. (2004). (*Right Panel*) Cumulative dark matter fraction as a function of radius for a sample of early-type galaxies with radial velocity measurements for discrete test particles in the outer halo (in this case, planetary nebulae). Also shown as solid curves are theoretical predictions from Λ CDM cosmological models with varying star formation efficiencies. Figure from Napolitano et al. (2009). In the coming decade, mapping the distribution of dark matter on galaxy scales will require observations and modeling using a variety of techniques, including weak and strong lensing, 2D integrated-light spectroscopy, radial velocity measurements of kinematic tracers, and X-ray observations.

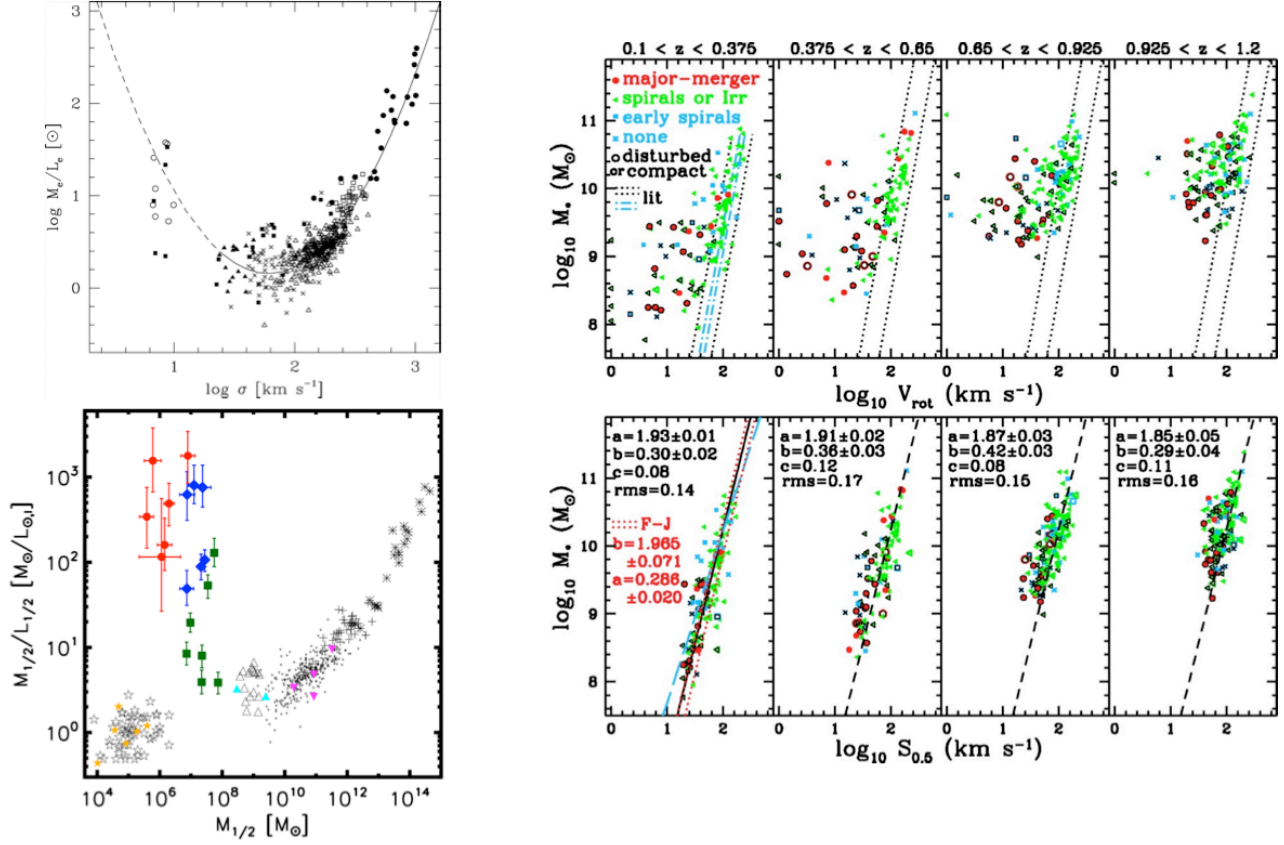


FIG. 3.— (Upper Left Panel) The M_e/L_e - σ relation of spheroids, showing effective mass-to-light ratio as a function of velocity dispersion from the scale of the intracluster light components in rich galaxy clusters down to dSph galaxies. This “fundamental manifold” fits the structural and kinematic properties of spheroids that span a factor of 100 in velocity dispersion and 1000 in effective radius. Figure from Zaritsky et al. (2006). (Lower Left Panel) Variation in half-light versus half-mass ratio for pressure-supported stellar systems using the mass estimator of Wolf et al. (2009) for the intracluster light components of galaxy clusters, brightest cluster galaxies, giant ellipticals, dwarf ellipticals, dSphs and globular clusters. Note the gradual but steady increase in mass-to-light ratio at the high-mass end, and a second, sharper, upturn below $\sim 10^7 M_\odot$. Figure from Wolf et al. (2009). (Right Panels) Stellar mass Tully-Fisher relations plotted as a function of rotation velocity, V_{rot} , and $S_{0.5} \equiv 0.5V_{\text{rot}}^2 + \sigma^2$ where σ is the velocity dispersion (upper and lower rows, respectively) for emission-line galaxies in the range $0.1 \lesssim z \lesssim 1.2$. Note that the lower relation is consistent with the stellar mass Faber-Jackson relation for low- z ellipticals in terms of slope and intercept, suggestive of a physical connection between the two relations. Figure from Kassin et al. (2007). Comprehensive models of structure formation must explain the observed scaling relations of galaxies, not just at the high-mass end, but over all mass scales. Characterizing these relations will be a top priority in the coming decade.

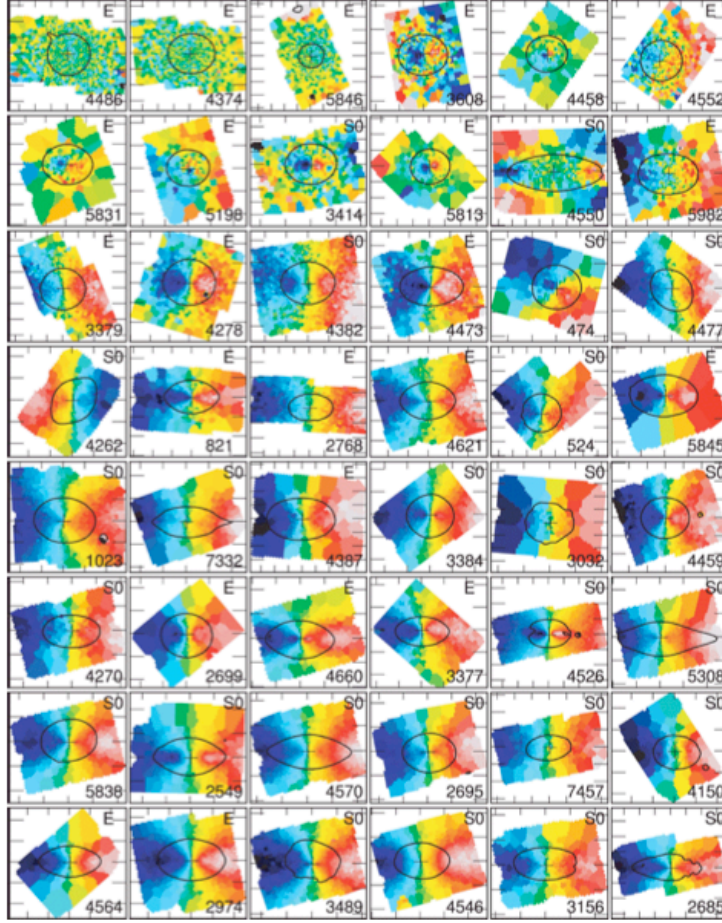


FIG. 4.— Stellar velocity fields for 48 nearby, early-type (i.e., red sequence) galaxies from the SAURON survey (with Hubble Types and NGC numbers shown in each panel). A representative isophote is overplotted in each thumbnail as a black solid line, and the centre is marked with a cross; tick marks correspond to $10''$. Galaxies are ordered by increasing $\lambda_R \equiv \langle R|V \rangle / \langle R\sqrt{V^2 + \sigma^2} \rangle$, a parameter that quantifies the observed projected stellar angular momentum per unit mass. Note the similarity in the velocity fields of the E and S0 galaxies. Figure from Emsellem et al. (2007). During the next decade, studies of the dynamics and angular momentum content of nearby galaxies will need to push beyond these pioneering observations — into the mass regime of dwarf galaxies, and well into the outer halos of high-mass galaxies, where much of their angular momentum may reside.

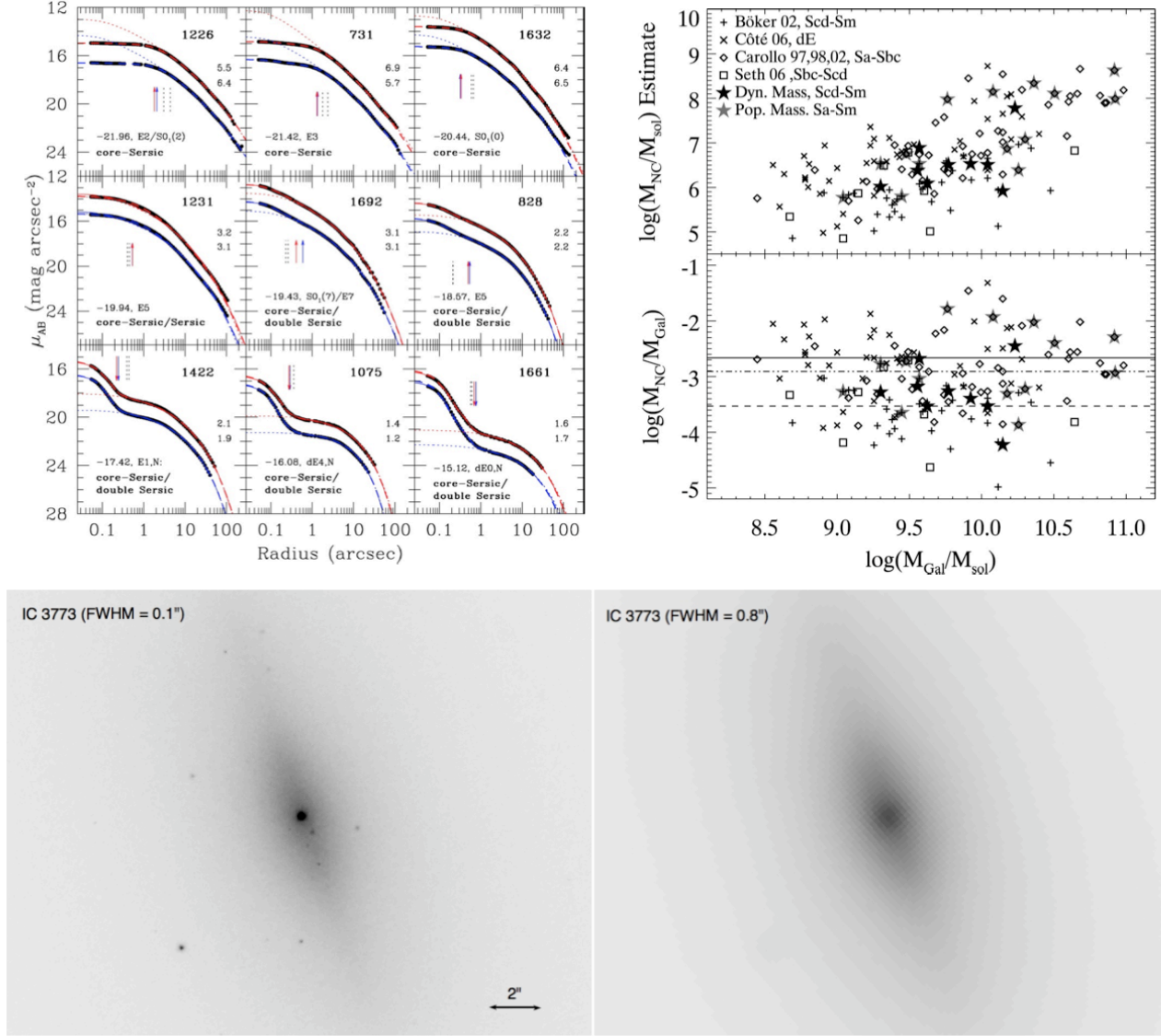


FIG. 5.— (Upper Left Panel) HST surface brightness profiles for nine early-type galaxies in the Virgo Cluster, spanning a range of ≥ 500 in blue luminosity. Identification numbers from the Virgo Cluster Catalog (VCC) are given in the upper right corner of each panel. Both g - and z -band profiles for each galaxy are shown as the lower and upper plots, respectively. The galaxies are ordered according to decreasing absolute blue magnitude, which is recorded in each panel, along with their morphological types and the best-fit Sérsic indices, n , for the galaxy measured in the g and z profiles (lower and upper labels). The dotted curves show the inward extrapolations of the Sérsic component that best fits the outer galaxy profile. Note the smooth transition from a central luminosity “deficit” to an “excess” (i.e., a structurally distinct stellar nucleus, or nuclear cluster) as one moves down the luminosity function. Figure from Côté et al. (2007). (Upper Right Panels) Nuclear cluster mass vs. galaxy mass for a sample of galaxies spanning a wide range in mass and Hubble Type (top). Ratio of nuclear cluster mass to galaxy mass (bottom). Overplotted are the median ratios for the elliptical galaxies (solid line), the early-type spirals (dot-dashed line), and the late-type spirals (dashed line). Figure from Seth et al. (2008). (Lower Panels) Comparison of HST/ACS imaging of the Virgo dwarf galaxy IC 3773 ($D \approx 16.5$ Mpc) to that available from the ground. Note the compact ($r_e \sim 4$ pc) stellar nucleus that is visible in the left panel. An angular resolution comparable to that of HST — with a stable PSF — is essential for studying stellar nuclei in nearby galaxies and understanding their relationship to the supermassive black holes that regulate AGN feedback.

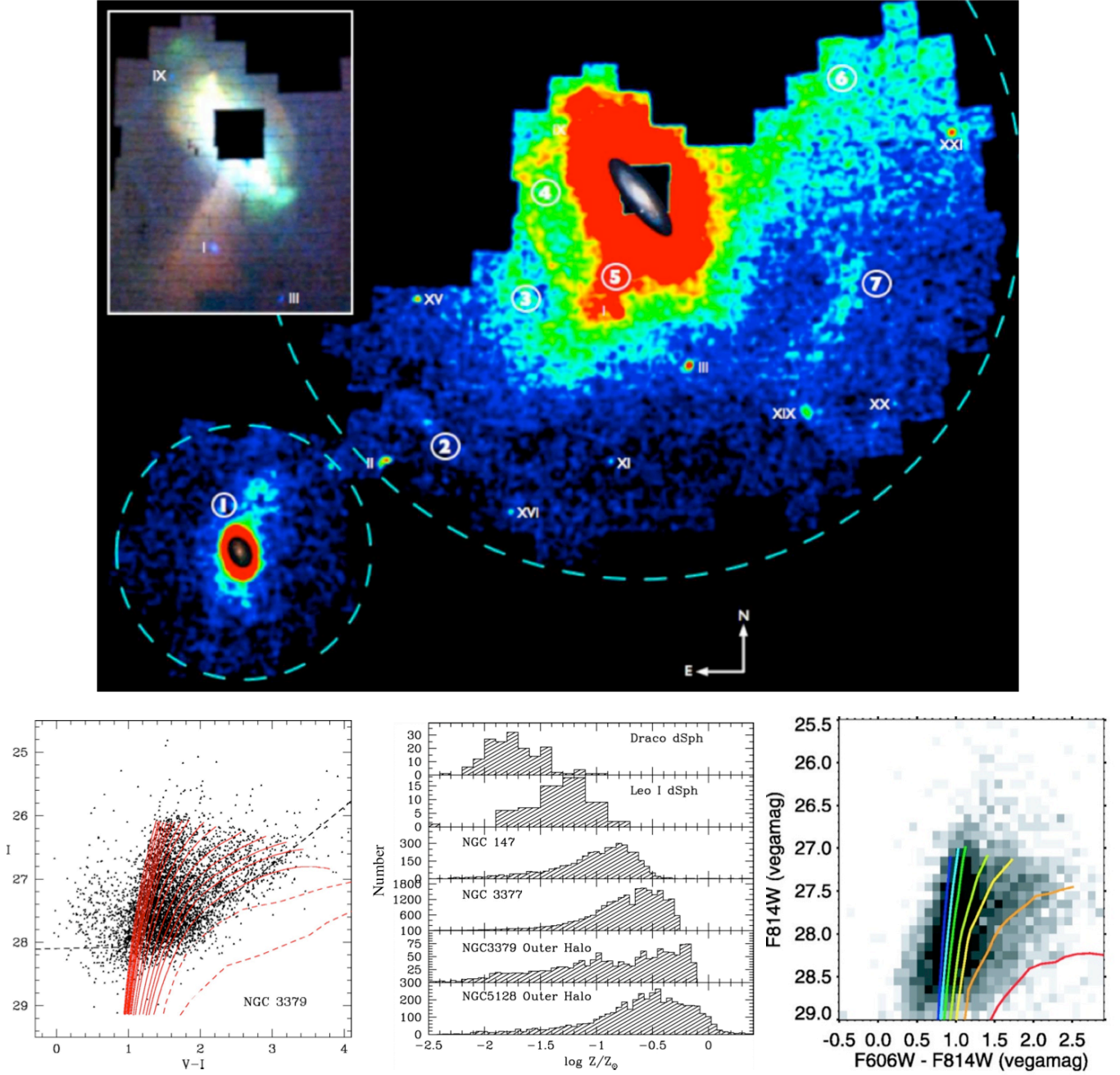


FIG. 6.— (*Upper Figure*) The distribution of RGB stars in the Local Group spiral galaxy M31 ($D \approx 0.8$ Mpc), derived from imaging with MegaCam on CFHT. The inset shows the central parts of the galaxy at higher angular resolution. Dashed circles represent the maximum projected radii of 150 and 50 kpc from M31 and M33, respectively. Scale images of the disks of M31 and M33 are overlaid. Note the striking abundance of substructure in the halo, including stellar arcs, streams and dwarf galaxies (some of which are labelled with roman numerals). Figure from McConnachie et al. (2009). (*Lower Left Panel*) HST color-magnitude diagram for the RGB stars in the halo of the elliptical galaxy NGC 3379 ($D \approx 11.0$ Mpc), with model tracks superimposed on the data points. These tracks assume a constant age of 12 Gyr, but different metallicities from $\log(Z/Z_{\odot}) = -2.0$ to $+0.4$ dex. (*Lower Middle Panel*) Metallicity distribution functions for six nearby early-type galaxies, including NGC 3379. Figures from Harris et al. (2007). (*Lower Right Panel*) Hess diagram for RGB stars in an intergalactic field in the Virgo Cluster ($D \approx 16.5$ Mpc), based on HST/ACS imaging (25-hrs in total). Model isochrones are overlaid. Figure from Williams et al. (2007). For galaxies beyond the Local Group, the measurement of star formation histories and metallicity distribution functions from resolved stellar populations will require a wide-field, optical/IR imaging space telescope.

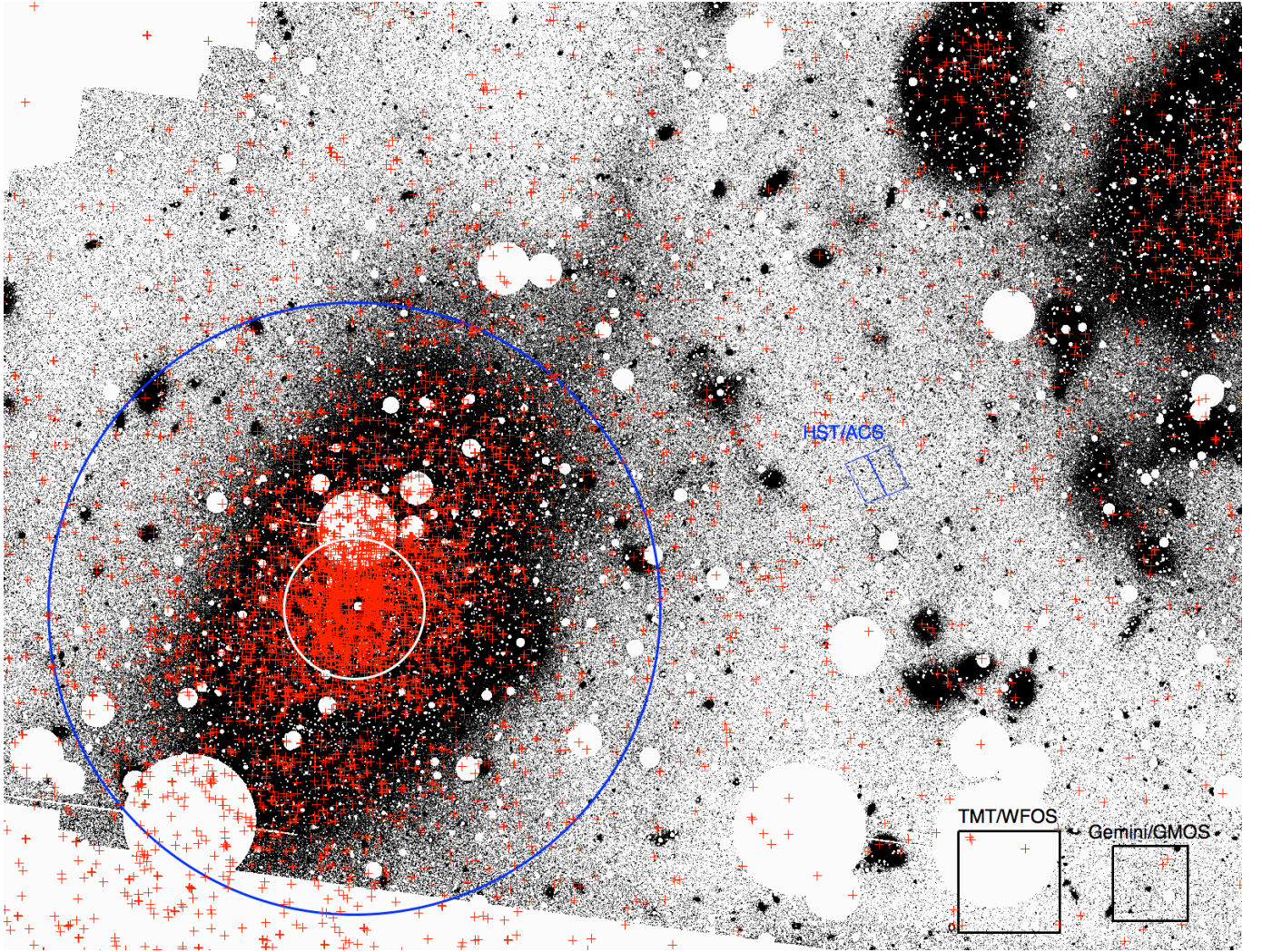


FIG. 7.— A map of the central region ($1^{\circ}2 \times 1^{\circ}5$) of the Virgo Cluster from Mihos et al. (2005), showing the diffuse light and the extended halos surrounding all large galaxies. The faintest features visible in this image have a surface brightness of $\mu_V \sim 28.5$ mag arcsec 2 . The crosses show the location of globular star clusters identified by the *Next Generation Virgo Cluster Survey*, which is currently mapping the entire Virgo Cluster with MegaCam on CFHT. Note that the image shown here covers $\lesssim 1\%$ of the Virgo Cluster. The large blue circle shows the field of view of the proposed diffraction-limited, 1m-class imaging space telescope described in Côté et al. (2009), while the smaller white circle shows the region where the enclosed dark halo mass is equal to that of the central galaxy, M87. The Virgo CMD shown in the lower panel of Fig. 6 is based on HST imaging in the field shown in blue. For comparison, the fields of view of TMT/WFOS and Gemini/GMOS are shown in the lower right corner. A wide-field imaging space telescope, working in tandem with a WFMOS-like instrument on an 8m-class telescope, will open an entirely new frontier in the study of galaxies, both locally and at high redshift.