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Early-type galaxies: Homogeneity in the local Universe
Galaxies have a wide range of luminosities, colors, masses, sizes, surface brightnesses, morphologies, star formation histories and environments. This diversity of properties is not surprising given the variety of physical processes which likely influence their formation and evolution. These include gravitational collapse, hydrodynamics, turbulence, magnetic fields, black-hole formation and accretion, nuclear activity, tidal and merger interactions, and evolving and inhomogeneous cosmic radiation fields. What *is* surprising is that although the properties we use to describe galaxies span a large "configuration space", galaxies do not fill it. Among all galaxy families, early-type galaxies show the most precise regularities in their observed parameters. Their spectral energy distributions appear to be virtually universal, showing very little variation with mass, environment, or cosmic time. What variations they do show are measurable and precise. Early-type galaxy colors, luminosities, half-light radii, velocity dispersions, and surface brightnesses are all correlated; they can be combined into a two-dimensional "Fundamental Plane" with very little scatter. I have used the Sloan Digital Sky Survey to make the definitive measurements of early-type galaxy scaling relations, and how they depend on environment, in the local Universe [4, 5, 18, 24, 25, 26]. These indicate that the gravitational potential energy of a galaxy is the most important physical quantity in determining its properties [19].

Early-type galaxies: Relation to quasars and black holes
The stars in early-types formed about ten billion years ago [14, 18, 26, 39]. This happens to be about the same time that quasars were most active in the Universe. Some of my recent work studies various aspects of this coincidence: for instance, if quasar activity is associated with accretion onto a black hole, then it may not be surprising that the most massive early-types in the local Universe host the most massive black holes [8, 15, 21]. My work has also shown how some correlations traced by black hole hosts are different from those defined by the bulk of the SDSS early-type galaxy population; ignoring this bias can lead to gross mis-estimates of the abundance of supermassive black holes in the universe [12, 13].

Early-type galaxies: Dry mergers and feedback
Although they are much less common than later type (e.g. spiral) galaxies, early-types account for most of the stellar mass in the Universe. Because they lack on-going or recent star formation, early-types today are said to be 'red and dead'. Understanding why has proved to be difficult. Numerical simulations of how structures form in an expanding universe suggest that early-type galaxies are assembled recently by mergers of less-massive galaxies of different ages, star formation histories, and gas contents. These hierarchical formation models assume a stochastic assembly history, making the homogeneity of the early-type galaxy population difficult to understand [26, 39]. Because massive objects are assembled more recently in such models, the problem is to arrange for star formation to occur at higher redshift than the actual assembly of the stars into a single massive galaxy (else they would not appear red and dead). The most recent models arrange for this to happen by a combination of two processes: dry mergers and feedback from the central black hole. The dry merger hypothesis assumes that the assembly of massive galaxies occurs by merging smaller progenitor systems of old stars without additional star formation (which would otherwise lead to bluer colors). This happens either because the merging units were themselves gas poor, or because feedback from the central black hole prevents the hot gas reservoirs of the progenitors from cooling and forming stars after the merger. Together, these processes allow massive galaxies to be built from smaller systems while still remaining red. The dry merger hypothesis is most necessary for the most massive galaxies [1]. Therefore, while at Penn, I have used the SDSS to assemble two different candidate samples for the most massive galaxies in the Universe: one sample assumes that

velocity dispersion is a good proxy for mass, whereas the other assumes that luminosity is the more reliable indicator.

-The HST-ACS Big-Sig sample: The first sample contains galaxies with extremely large velocity dispersions (σ) [17]. Such objects are rare [22], so a large volume was required to find them. I was awarded Hubble Space Telescope (HST) time to observe about 50 of the objects with the largest velocity dispersions in the local universe ($350 < \sigma < 500$ km/s drawn from the SDSS database). These systems appear to be of two distinct types [6,7]: the less luminous objects are rather flattened, and their properties suggest some amount of rotational support. These objects are extremely dense for their luminosities, suggesting wet (rather than dry) merger histories with abnormally large amounts of gaseous dissipation – however, because of their rotation, the large estimated velocity dispersions do not imply large masses. The more luminous objects in this sample tend to be round and to lie in or at the centers of clusters. Their circular isophotes, large velocity dispersions, red colors and dense environments are consistent with the hypothesis that they formed from radial mergers, so they are now massive prolate objects which we happen to have viewed along the major axis.

-BCGs and minor dry mergers: The second sample contains the most luminous galaxies in galaxy clusters (usually called Brightest Cluster Galaxies, these are typically ten or twenty times brighter than any of the other galaxies in their cluster) [3, 16]. I showed that BCGs tend to have larger than expected sizes for their optical luminosities [16], suggesting formation histories with below average dissipation—i.e. consistent with the dry merger scenario. Recently, I showed that the sizes and velocity dispersions of massive early-type galaxies are evolving even at small look-back times, and that the sizes are approximately independent of age [3]. The recent rapid evolution in size and velocity dispersion suggests formation histories dominated by many minor dry mergers rather than a few major mergers – mine is the first observational paper to point out this potentially important shift in paradigm for understanding these objects.

Future work: Color gradients

Typically, early-type galaxies are redder in the center than they are further out; these color gradients are expected to encode information about the formation history of an object. In particular, larger gradients are expected if these objects formed from a single monolithic collapse—repeated mergers are expected to scramble the gradients originally present in the merging subunits. However, color gradients of BCGs have not been studied. Therefore, as a next step towards testing the dry merging scenario we have initiated a study on color gradients in BCGs and other massive galaxies. Color gradients are expected to depend on wavelength, so our study will use ground and space-based imaging in the ultra-violet, optical and infra-red (about which, see below).

2MASSDSX: A homogeneous, panchromatic catalog of galaxies

A consensus has been reached that a homogeneous catalog which spans a wide wavelength range can provide invaluable information on many aspects of galaxy formation models: the ultra-violet and optical colors constrain star formation history and AGN activity, whereas optical and infrared colors constrain mean ages, metallicities and stellar masses. I have recently been funded to generate such a database of galaxies, with wavelength coverage from the UV to the NIR, in the local universe. This project will compile a sample of about 80,000 galaxies which have been observed in the NIR, optical and NUV by 2MASS, the SDSS and GALEX (hence the acronym 2MASSDSX), and for which reliable fits to the surface brightness profile can be made. Homogeneous photometric reductions in all the passbands, using algorithms developed at Penn in collaboration with my student (J. Hyde) and postdoc (N. Roche), will be made. This database will serve as the benchmark against which data from the next generation of high redshift surveys will be compared, thus constraining how galaxies formed.

Future work: Evolution and environment
In hierarchical formation models there is a close connection between galaxy evolution and environment: evolution is expected to have been more rapid in overdense regions. That is to say, the objects in the densest regions of the universe should be older than those in less dense regions. The next generation of sky surveys will allow precise tests of this prediction. This is because they will image galaxies at a time when the Universe was less than half its present age. Hierarchical models suggest that the stellar populations in the most massive galaxies today, which populate the densest regions of the local Universe, have not changed significantly in the last few billion years, whereas less massive galaxies have evolved more significantly. I will use zCosmos as well as the next generation of surveys (e.g. DES) to quantify this *differential* evolution relative to my 2MASS-DSX sample. By combining both evolution *and* environment, I expect to provide a sharp test of hierarchical formation models.

Future work: Patchy HeII reionization?
In 2003, I discovered a feature in the spectra of high redshift quasars [28, 29], the strength and duration of which appeared to be consistent with models of the ionization of Helium's second electron (hence the II in HeII). Although the validity of this feature in the SDSS dataset was initially questioned, a similar feature has now been seen in two very different datasets – high S/N spectra obtained from the Keck and Magellan telescopes, for which the analysis techniques and systematic effects are completely different. In the meantime, modelers are now finding it more difficult to explain the feature! The SDSS dataset is now 7 times larger than it was in 2003, making it 80 times larger than the Keck-Magellan high-resolution sample; it will remain the largest available dataset with which to study HeII reionization for at least the next decade. This dataset is large enough to study if the signal varies across the sky, helping to confirm if it is indeed due to HeII. If so, then the patchiness of the signal can be used to constrain models of the sources of the ionizing photons. I have recently been funded to do this analysis.

Synergy with the astrophysics program at Penn
The next generation of surveys will provide constraints on the nature of Dark Energy in the Universe. These will come primarily from four types of measurement: the abundance and evolution of galaxy clusters, the evolution of galaxy clustering, weak gravitational lensing, and measurements of supernovae brightnesses as a function of redshift. Experts in several of these methods are already in-house at Penn (Devlin, Sheth, Bernstein, Jain, Sako), which is a member of the Dark Energy Survey. Because early-type galaxies are big and bright, they can be seen to large distances, so they will play a key role in the first two of these methods. Therefore, my primary research interest, the formation of massive galaxies, represents an important synergy at Penn. By providing a better understanding of early-type galaxy formation, my work helps to ensure that, for the first two tracers of dark energy at least, cosmological conclusions will be less clouded by concerns about the effects of evolution. In addition:
-I am currently collaborating with Masao Sako and his student on a study of whether or not supernova rates (and other properties) depend on galaxy type (and environment).
-My discovery of a feature in the Ly-α forest is something which Adam Lidz is in the process of modelling.
-And finally, I mentioned earlier that the reionization of HeII depends on the ionizing background. This, in turn, encodes information about the epoch at which Hydrogen was reionized. Hence, my measurement will also provide useful constraints on models which seek to explain the signal that the next generation of 21 cm measurements hope to see. James Aguirre is involved in one of these 21 cm projects.