My research interests concentrate around the structure and dynamics of galaxies and their origin in the processes of galaxy formation and evolution. Cosmological structure formation models lead to a picture in which galaxies form by baryonic collapse within dark matter halos, and hierarchical assembly of halos can drive accretion onto galaxies and galaxy evolution. The signatures of these processes can be observed both in present-day galaxies and in the evolution of galaxy properties as a function of redshift. I outline research programs which measure galaxy structure and kinematics both at high z and locally, with the aim of testing current models and simulations of galaxy formation.

Galaxy evolution to $z = 1.5$: structure and internal kinematics of galaxies

The process of galaxy formation is one of the major open problems in astrophysics today. In hierarchical structure formation, overdensities on small scales collapse earlier and aggregate to form larger structures. Large scales are in the linear regime and relatively well understood, but galaxies are non-linear perturbations. N-body simulations are beginning to be able to simulate the formation of individual galaxies, but messy astrophysics such as star formation must be put in by hand (e.g. Navarro & Steinmetz 2000). Another approach is to produce analytic models for the collapse of baryons within a dark halo (e.g. Fall & Efstathiou 1980; Dalcanton *et al.* 1997; Mo *et al.* 1998). Both varieties of model have some success in reproducing properties of observed galaxies, such as the slope of the Tully-Fisher relation. However, strong tests of galaxy formation models must also come from measurements of galaxy evolution.

Surveys of galaxies to redshifts $z \sim 1$ reach to half the present age of the universe, and probe an epoch where evolutionary effects are significant. At $z \sim 1$, mergers are more frequent and the star formation rate is ~ 10 times higher than today, and galaxies can be studied in detail using ground-based spectroscopy and HST imaging (both much more difficult at $z > 1.5$). At Santa Cruz, I have been working with the DEEP (Deep Extragalactic Evolutionary Probe) project on surveys of galaxies to $z \leq 1.5$. The DEEP 1 survey has redshifts for 625 galaxies with HST VI imaging in the Groth Survey Strip; the DEEP 2 survey begun in Fall 2002 has so far confirmed redshifts of 8000 galaxies, mostly at $0.7 < z < 1.5$, and will reach 50,000 galaxies over 3 years. Figure 1 shows the space distribution of about 2500 galaxies in the Extended Groth Strip area of DEEP 2.

My chief projects within the DEEP survey are (1) the distribution of galaxies in luminosity, color and structural parameters (bulge/disk, concentration), and its relation to environment; and (2) the luminosity-mass relation, as traced by internal kinematic linewidths and rotation curves.

Color, luminosity, and environment: Figure 2 shows the colors of DEEP2 galaxies with redshift, and Figure 3 shows the distribution of DEEP1 galaxies in luminosity and restframe color, and the breakdown into bulges and disks from HST photometry. There is a bimodality in color, and a strong difference in the luminosity functions of red and blue galaxies, with few or no faint red galaxies. A similar bimodality and color-luminosity relation are seen locally by the SDSS survey (Blanton *et al.* 2002, Kauffmann *et al.* 2002) and to $z = 1$ by the COMBO-17 photometric redshift survey (Bell *et al.* 2003). The color-luminosity distribution gives insight into galaxy formation histories; for example, the brightest red galaxies are brighter than the blue galaxies, so the observed blue galaxies cannot fade to produce the observed red population.

The HST imaging of the Groth Strip allows us to measure galaxy structural parameters and do bulge and disk decompositions (Simard *et al.* 2002). Red galaxies are strongly correlated with the presence of a luminous, red bulge, as shown in Figures 3 However, they are not all ellipticals; the division is at $U - B = 0.15$, the color of an Sab galaxy.

The red galaxies are not simply an "old, red and dead" population in which star formation ended long ago; their bulges are old, but many have disk colors indicating ongoing star formation, similar to the Milky Way. The existence of a division in total color is still a puzzle: for any size red bulge there is some disk which could yield $U - B = 0.15$, but this combination is disfavored. Equivalently one could regard the total color as a measure of present day star formation rate per total stellar mass; again it is not obvious why a particular specific SFR is disfavored and why the dichotomy is constant with z.

The color-luminosity distribution and its evolution will yield strong tests of galaxy formation models. These sharpen the classic problem of CDM models, which is that small overdensities collapse first, yet locally we observe that large galaxies are old and small galaxies are young; the DEEP data extend this dilemma to $z > 1$. The resolution likely lies in the morphology-density relation, and the fact that overdense environments collapse first. Figure 1 suggests that the red galaxies are more clustered, and this is borne out by measurements of the correlation length (Coil *et al.*, ApJ submitted).

We are collaborating with modelers to explore whether semi-analytic models can naturally predict the color dichotomy and its persistence with z. The data coming from the DEEP 2 survey enable us to reinforce these measurements with a much larger sample extending to $z = 1.5$, although HST imaging will only be available for a subset.

Kinematics and Tully Fisher relations: I am also using DEEP data to measure the galaxy mass-luminosity relation. At low z, the Tully-Fisher relation between luminosity and rotation velocity, $L \propto V_c^\alpha$, $(\alpha \sim 3 - 4)$ must be reproduced by any reasonable formation model. Since the T-F is a one-parameter relation, unlike the Fundamental Plane of ellipticals and the virial theorem, it must reflect some constraint from the formation process.

I have been exploring a T-F analog, the luminosity-linewidth relation. Many high-z galaxies are spatially unresolved, so instead of V_c we measure the velocity dispersion σ of the integrated line emission. The magnitude-linewidth $(M_B - \sigma)$ relation for a subset of DEEP 2 galaxies is plotted in Figure 4 (Weiner *et al.* 2002). The upper diagonal line in the first panel shows a fit to low-z data from DEEP 1, similar to a $z = 0$ T-F relation. The other is a fit to the $0.65 < z < 0.8$ data, and shows an offset in zeropoint.

At high z it is clear that the points move below the low-z relation, in the sense of lower σ or brighter M_B, and the slope of the T-F relation flattens. This is not merely a selection effect,[1] since we are measuring a relation $\sigma(M_B)$ and there is not a selection toward low/high σ. The evolution is substantially larger than is seen in DEEP 1 Tully-Fisher samples which are restricted to large, well-defined disk galaxies (Vogt *et al.* 1997).

Some possible interpretations of this shift include: (1) galaxies are brighter but change little in total mass at $z \sim 1$; (2) the high-z sample includes a population which was brighter for a given σ and is not common today; (3) linewidths at high z are less representative of the mass, if σ only probes the galaxy nucleus in a starburst. We are currently exploring methods to discriminate among these interpretations: for example, the shift in $\sigma(M_B)$ is only weakly correlated with galaxy color and emission line strength, arguing against nuclear starbursts

[1] As opposed to e.g. the selection effects that are very important in attempts to measure evolution in the magnitude-size distribution (Simard *et al.* 1999).

as a sole explanation.

I am continuing this project with DEEP 1 and 2 data, and am heavily involved with DEEP 2 spectroscopy, redshift and linewidth measurement. Since DEEP 2 observations are projected to take 3 years, I anticipate a continuing association with the project after leaving Santa Cruz. DEEP 2 observations of 50,000 galaxies, some fraction with HST imaging, will provide a tremendous sample for measurement of linewidths and evolution to $z = 1.5$.

Further projects: In addition, I will develop projects which use the DEEP samples as a starting point, but extend the data and modeling to create independent tests. The Extended Groth Strip field is the target of large surveys by the SIRTF and GALEX satellites, and we are collaborating with those teams to combine DEEP spectroscopy with the infrared and UV data. These will include both dynamical and stellar mass measures, and multiple star formation rate indicators.

Another project we are exploring is the use of integral-field unit (IFU) spectroscopy on large telescopes to measure internal kinematics of high-z galaxies. Because mergers and clumpy-looking galaxies are much more common at $z \sim 1$, it is not clear whether high-z galaxies generally have ordered rotation, or chaotic, infalling motions. The HST Groth Strip DEEP 1 survey has many $z \sim 1$ galaxies that look like well-formed disks, and many peculiar, clumpy, or merging objects. We are investigating the use of IFUs such as those on Gemini-GMOS, and forthcoming on Keck and other telescopes to obtain 2-D resolved spectroscopy of galaxies with HST imaging. I expect that advances in adaptive optics and IR spectroscopy will make narrow-band imaging and 2-D, resolved spectroscopy of distant galaxies a burgeoning field in the near future.

Internal kinematics of galaxies: dark and luminous mass distribution

Scenarios of galaxy formation motivated by observations of Galactic structure (*e.g.* Eggen, Lynden-Bell, & Sandage 1962, Searle & Zinn 1978), and theoretical studies such as N-body simulation of hierarchical structure formation in CDM universes (*e.g.* Cen & Ostriker 1993, Navarro *et al.* 1996), have developed largely independently. A major difficulty in linking the two is that observations probe the luminous matter in galaxies while simulations are driven by the dark matter. We do not even know how the size and mass of a galaxy correspond to the mass of its dark halo.

The most ironclad evidence for dark matter halos around galaxies comes from extended H I rotation curves $V_c(R)$, which are nearly flat, showing that the enclosed mass continues to grow with radius beyond the optical disk. However, a typical rotation curve can be fitted well with either a massive disk and a dark halo which is only important at large Galactic radius, or a dark halo that dominates at all radii (van Albada *et al.* 1985). As a result we do not really understand the structure of disk galaxies and we do not know the dark halo mass corresponding to a given V_{circ}. This last point is particularly important for comparison to the Press-Schecter formalism and to cosmological N-body simulations.

I have developed (with collaborators Ted Williams, Jerry Sellwood, & Jacqueline van Gorkom) a method to determine the disk mass of a barred galaxy and hence to lift the degeneracy, measuring the dark halo mass. In a barred galaxy, the potential of the ellipsoidal stellar bar causes non-circular streaming motions, which are observable as shocks in the gas velocity field. The streaming motions depend directly on the mass of the stars in the bar. By comparing observations to a series of fluid-dynamical simulations in different potentials, we measure the bar mass-to-light ratio (M/L); see Figure 5.

In NGC 4123, the galaxy on which we carried out this program of observation and simulation, we found that the stellar disk has a high M/L, requiring a dark halo which is much less centrally concentrated than predicted by CDM simulations (Weiner *et al.* 2001a,b). We have now confirmed that another barred galaxy, NGC 3095, has a high stellar M/L and a low dark matter central density (Weiner 2003), shown in Figure 6. Thus the problem of low dark halo central densities found in dwarf and LSB galaxies (e.g. de Blok *et al.* 2001) also exists in bright HSB galaxies.

In fact, as Figure 6 shows, the HSBs are so baryon dominated that their halo dark matter densities are below those in the LSBs, which are already below CDM predictions (Alam *et al.* 2002). However, the baryonic collapse in HSBs should have drawn in the DM and raised the dark matter density. This is a very serious problem, most likely not with the CDM power spectrum, but with standard collapse models for disk galaxy formation; a possible resolution is angular momentum transfer between baryons and dark matter, but this may cause as many problems as it solves.

Other projects

Evolution of barred galaxies: 30-70% of disk galaxies have stellar bars (more in the IR, Eskridge *et al.* 2000). Bars are generally thought to arise from a collective instability of the stellar disk. However, it is not known whether bars are long-lasting or come and go, how they drive secular evolution of the disk and bulge, nor why some galaxies are barred and others not. Although it is relatively easy to detect bars in present-day galaxies, the hard question is how to tell if a galaxy has had a bar in its past. Gas-dynamical simulations predict that bars clear out a several-kpc hole in the inner galaxy (e.g. Athanassoula 1992, Weiner *et al.* 1999,2001a). An unbiased 21cm H I sample of galaxies shows a strong correlation between bars and H I holes, implying that bars are long-lasting; an ex-barred galaxy would be expected to have an H I hole but no bar, but no such galaxies were found. Further directions of this project include more gas-dynamical simulations of bar and spiral-arm torques, larger H I samples and linkage with CO observations of molecular gas, and potentially searches for abundance-gradient and stellar-dynamical signatures of an ex-bar.

X-ray gas halos of spirals: While elliptical galaxies are known to have large halos of hot, X-ray emitting gas, searches have found smaller or no X-ray halos around spiral galaxies. This is potentially contrary to expectations (Benson *et al.* 2000; Sommer-Larsen *et al.* 2002). I used the XMM satellite (with collaborators Rebecca Bernstein and John Mulchaey) to observe the giant LSB galaxy Malin 2, which has $L_B = 6L^*$. X-ray emission was detected but is from disk sources; the upper limits on a hot gas halo are well below the $L_X - \sigma$ relation for groups of galaxies with similar luminosity and σ (Mulchaey & Zabludoff 1998). Giant LSBs seem to be effectively "failed groups," with similar mass but higher spin, having formed from high angular momentum initial perturbations (Burstein *et al.* 1997). The X-ray properties may be determined by the merging history, and this could provide a test of whether modern N-body+hydro simulations treat gas cooling and feedback properly.

Distribution of galaxies and intergalactic O VI gas: Extremely low-density gas pervades the space between galaxies, but this IGM is so tenuous that it is detectable only in absorption.At low redshift, 30–50% of baryons are predicted to lie in a "warm-hot" IGM, at $T \sim 10^{5.5}$ K (Dave *et al.* 1999; Cen *et al.* 2001). Unfortunately, gas at this temperature is nearly unobservable, except in the far-UV absorption doublet of O VI ($\lambda\lambda$ 1032,1038 Å). Recently O VI absorbers have been detected in far-UV spectra taken with the HST and FUSE satellites (e.g. Tripp *et al.* 2000). The number detected implies that the warm-hot IGM dominates the baryonic mass – but is subject to clustering and cosmic variance. Additionally, it remains unclear whether these O VI absorption systems represent the warm-hot IGM, or are more closely affiliated with galaxies and groups of galaxies. I am collaborating on a project led by Jason Prochaska (UCO/Lick) and Hsiao-Wen Chen (MIT) to do galaxy redshift surveys in the fields of QSOs observed with FUSE and STIS. We will use the galaxy redshifts to determine galaxy-O VI absorber impact parameters and correlation lengths, and the relation of absorber and galaxy clustering.

Teaching and public outreach

During my time at Rutgers I taught sections of introductory physics and physics laboratory classes, 3-4 sections each of ~ 25 students per week. I also helped staff our public rooftop observing nights, which included visual and telescope observing (8" Celestron-type and our 20" reflector). Visitors included students in introductory astronomy and a wide variety of the general public, with well over 100 people at times for unusual or publicized events (e.g. lunar eclipses, Comet Swift-Tuttle).

While it can be challenging to teach physics and astronomy especially to encourage interactivity between students and instructors, I find it an rewarding and different set of challenges from those presented by research activities. Furthermore, I believe that teaching and public outreach activities are necessary for astronomers to share our interest in the subject and keep the public interested.

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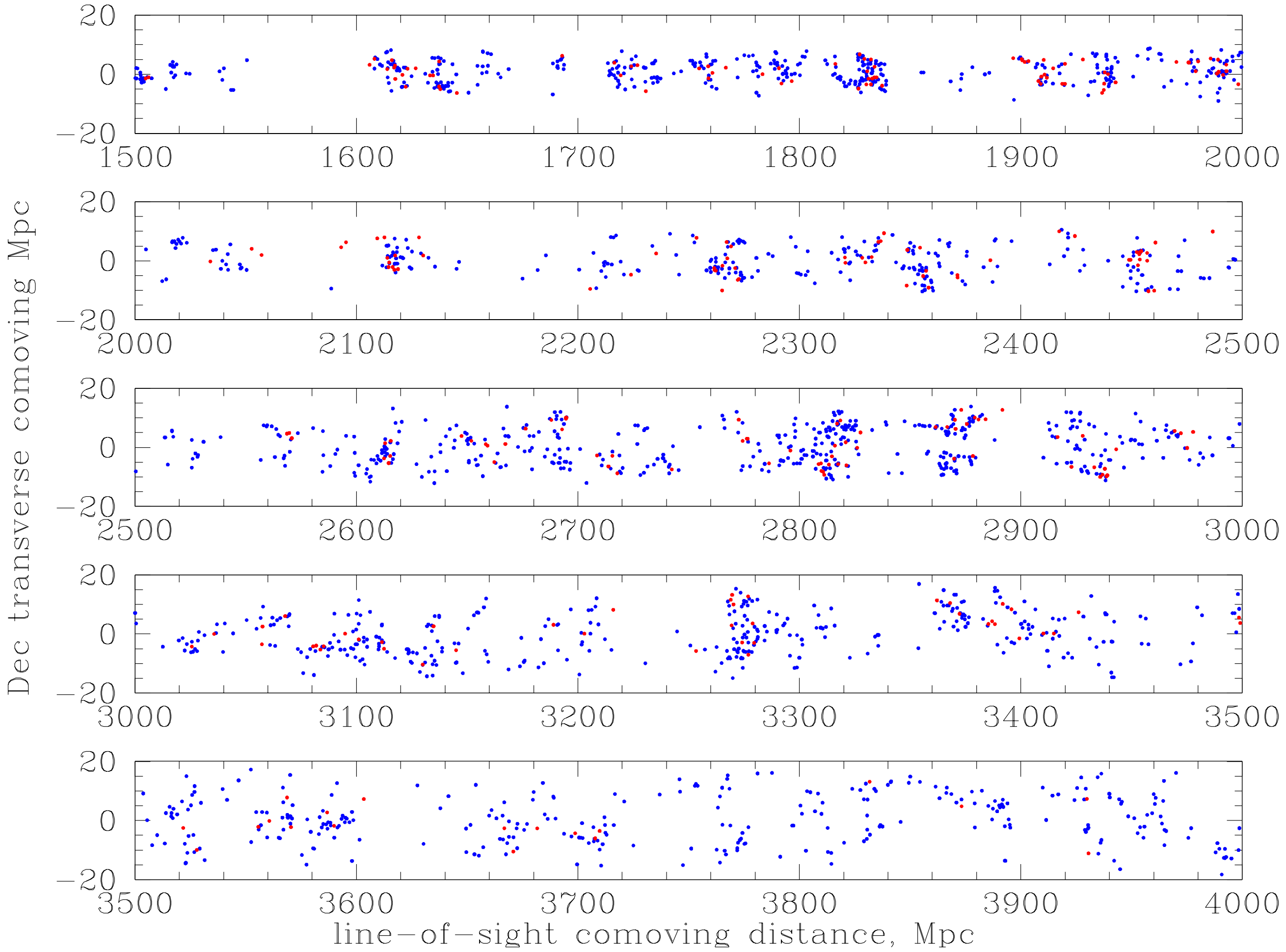

Figure 1: Space distribution of DEEP 2 Extended Groth Strip galaxies
The distribution of galaxies in comoving Mpc in the EGS, from 1500 to 4000 comoving Mpc, roughly $0.4 < z < 1.3$, coded by restframe color. These galaxies are roughly 25% of the total number to be obtained in the EGS. Note the large-scale structure, with walls covering the whole survey, and the difference in clustering of red and blue galaxies.

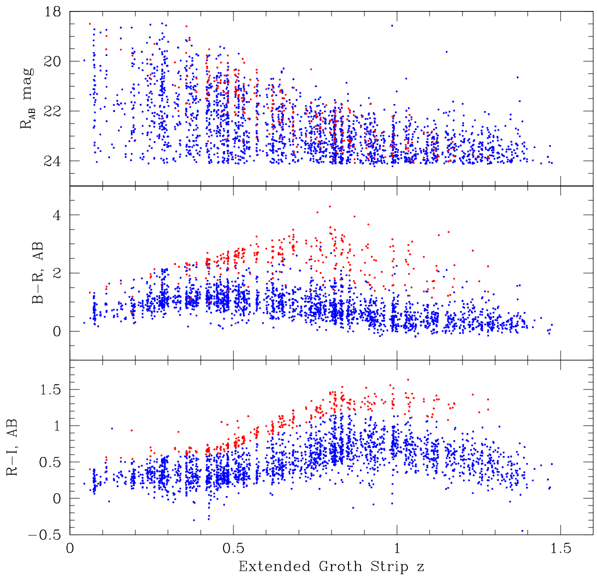

Figure 2: Apparent magnitude and color versus redshift for DEEP 2 Groth Strip galaxies The points are coded red/blue by total galaxy color, split at $U - B(AB) = 1.1$, and show a red/blue bimodality in the galaxy distribution. The falloff in red galaxies at high z is at least partly due to the magnitude limit.

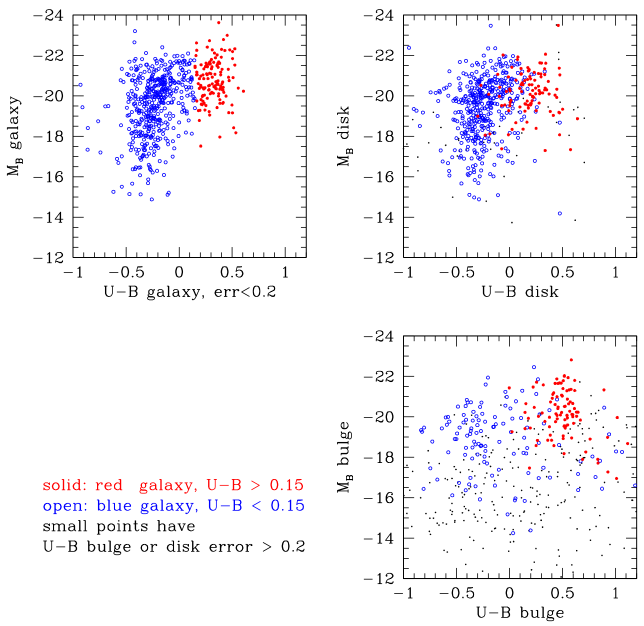

Figure 3: Restframe color-luminosity distribution for DEEP1 galaxies, bulges, and disks HST imaging allows photometric bulge/disk fits for the DEEP 1 Groth Strip. The points are coded red/blue by total galaxy color, showing the red/blue bimodality in the galaxy distribution, and no faint red galaxies (not merely a selection effect). Red galaxies have luminous, red bulges; a second population of fainter blue "bulges" are likely star-forming centers.

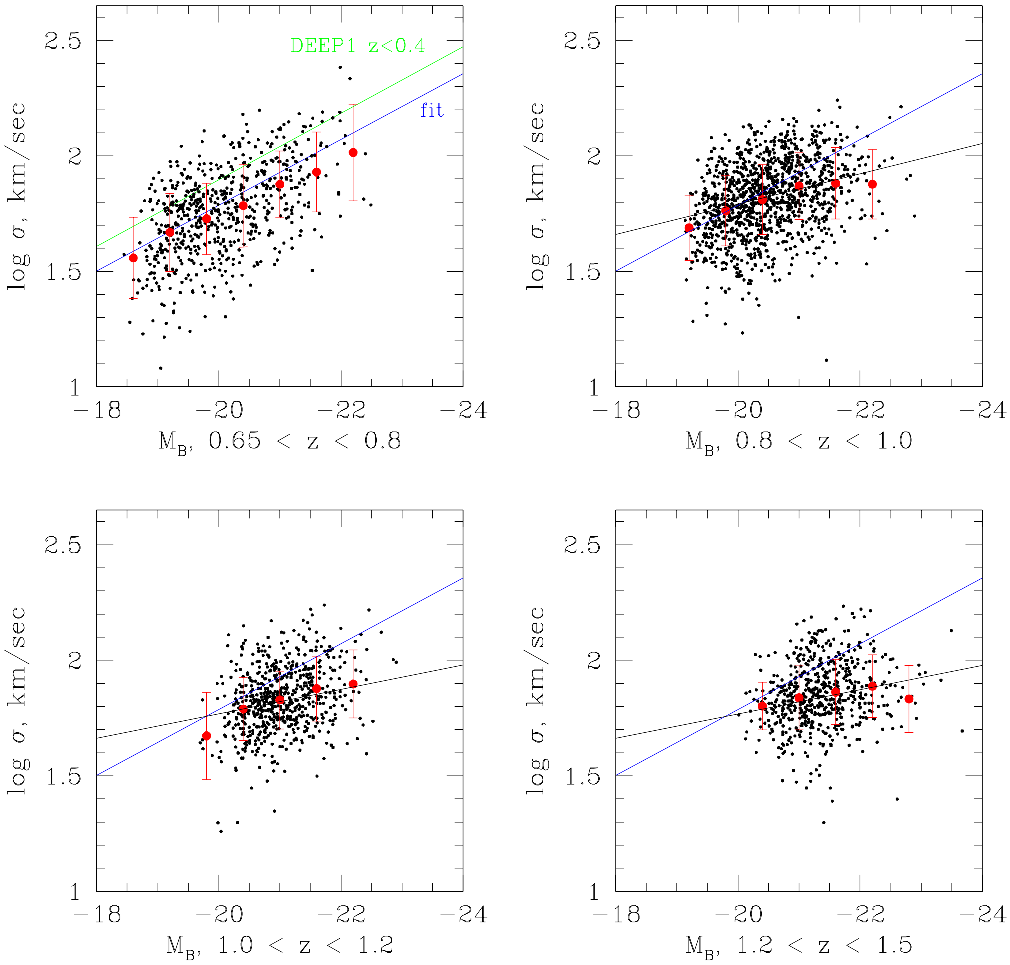

Figure 4: Evolution in the linewidth-magnitude relation of field galaxies. Velocity linewidth (log dispersion σ) versus rest-frame M_B for 3280 galaxies from the DEEP 2 Survey, in four redshift ranges. The upper, green diagonal line is a fit to DEEP1 low z data, the blue line is a fit to DEEP2 $0.65 < z < 0.8$ data, and the black lines are fits to the data in each redshift bin. The large points are mean log σ in bins of magnitude. Strong evolution is seen in zero point and slope. Galaxies at high z lie below and to the right of the low-z line, consistent with galaxies of similar mass (and σ) being brighter in the past.

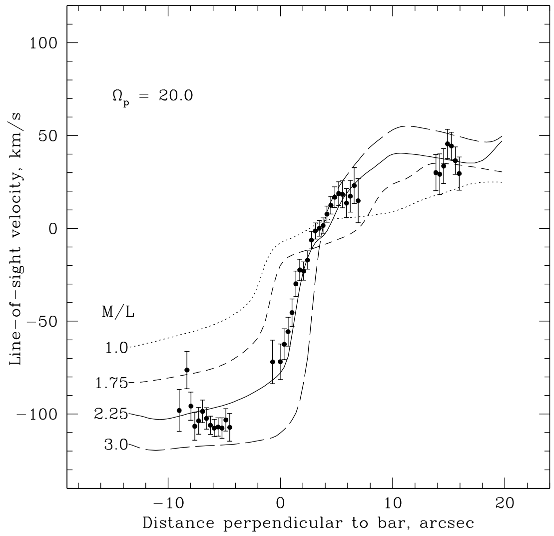

Figure 5: Observed and model velocities across the bar shock in NGC 4123
The points are the observed Fabry-Perot velocities and the lines are from simulated velocity fields for models with different values of disk M/L_I. As disk M/L_I is increased, the magnitude of the shock increases; M/L_I= 2.25, near maximum disk, provides a good fit.

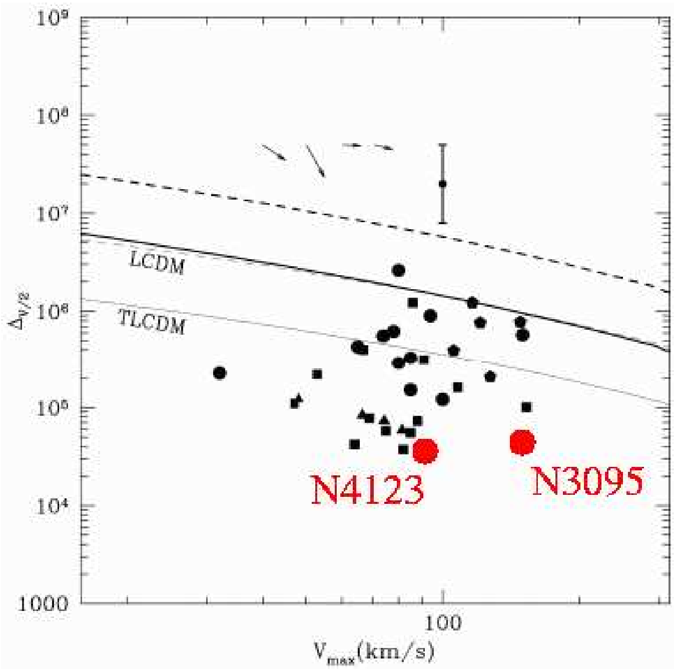

Figure 6: Dark halo mean density versus maximum velocity
Figure 2 of Alam *et al.* (2002) plots a measure of the dark halo mean density within a fiducial radius, $\Delta(V_{max}/2)$, versus rotation velocity V_{max}. The upper curve is a prediction of a standard ΛCDM model and the lower curve is a tilted model with less power on small scales. Black points are upper limits from low surface brightness galaxies. We have overplotted red points for our measurements of the dark halos in two HSB barred galaxies. These are lower DM density than even the LSB galaxies and much below the N-body predictions.