My recent research projects study galaxy evolution with emphasis on star formation histories, gas accretion and outflow, and galaxy kinematics. I am working on projects that study both low and high redshift galaxies, with emphases on linking low redshift and high redshift objects (e.g. using large surveys to find low-z analogs for high-z galaxies) and on studying the links between phases of galaxy evolution (e.g. mergers, IR-luminous galaxies, QSOs).

These projects use data from large redshift surveys, including SDSS at \( z \sim 0.1 \) and DEEP2 at \( z \sim 1 \), and multi-wavelength data including HST, Spitzer and Herschel mid- and far-infrared, and Chandra X-ray observations. Much of this work attempts to understand the \( z \sim 1 \) universe, where the star formation rate was \( \sim 10 \times \) higher than today, and link it to the galaxies we see today. This leverages my prior experience working on both local and high-redshift galaxies. I have also worked in instrument building and software, and am interested in participating in future optical, IR or radio instrument projects.

I have focused recently on far-IR observations that probe dust and emission lines from star-forming regions, and will continue to work with the wealth of data coming from Spitzer and Herschel. In the near future this field will be revolutionized by sub-mm and radio telescopes (e.g. ALMA, CARMA, IRAM, EVLA, Scuba-2 and eventually CCAT), enabling direct probes of gas, SFR and dust content in distant galaxies. I have begun projects in this area through a Herschel program of spectroscopy of far-IR lines from star forming regions in IR-luminous disk galaxies, described below, and with involvement in an IRAM Large Program to measure gas mass through CO detections in \( z > 1 \) galaxies (Tacconi et al. 2010).

**Background:** We now have a basic physical model of galaxy formation, driven by the collapse of gas inside dark matter halos, and we have measured global evolution in the higher star formation rate and frequency of quasars at redshifts \( z = 1 - 3 \). But we do not understand nearly as well the detailed evolution of the galaxy population: how galaxies we observe at high redshift are transformed into today’s universe, or how various evolutionary stages (e.g. quasars, mergers, infrared-luminous galaxies, ellipticals, spirals) are linked, or how gas infall and outflow governs galaxy metallicity and IGM enrichment. Measuring the physical properties of galaxies, their scaling relations, clustering, and the links between populations provides key input to constrain galaxy formation models, since the physics are too complex to simulate *ab initio*. Here I outline several programs to measure links between star forming galaxy populations, their environment, and their descendents.

1. **Physical conditions in high-SFR galaxies at low and high redshift**

   Infrared-luminous galaxies are powered by star formation or AGN radiation reprocessed by dust, and include the highest star formation rate (SFR) galaxies in the local and \( z \geq 1 \) universe. At \( z \sim 1 \), luminous and ultra-luminous IR galaxies (LIRGs and ULIRGs, \( L_{IR} > 10^{11} \) and \( 10^{12} L_{\odot} \)) are much more common than locally (e.g. Le Floc’h et al. 2005). Locally, many LIRGs and the vast majority of ULIRGs are major mergers (Sanders & Mirabel 1996), but this is more controversial at higher redshift (e.g. Lotz et al. 2008). Understanding the nature of these higher-z galaxies is necessary to understand the conditions and environments in which the bulk of stars in massive galaxies formed.

   There are signs that the relation of IR spectral shape to IR luminosity is different at \( z > 1 \) than locally (e.g. Papovich et al. 2007; Elbaz et al. 2011). This may be caused by different physical conditions in the star forming regions, e.g. gas density, radiation field, or dust temperatures. At \( z > 1 \), many LIRGs appear to be disky rather than mergers, suggesting lower SFR surface density. Recent work by an Arizona graduate student, using sizes from radio interferometry to measure the spatial extent of star formation, shows that high-z U/LIRGs are indeed large diameter, while local ULIRGs are very centrally concetrated (Rujopakarn et al 2011).

   Far-IR fine structure lines such as [C II] \( 158 \) \( \mu m \) and [O I] \( 63 \) \( \mu m \) can probe the density and
ionization in star forming regions. The $[\text{C II}]/L_{\text{IR}}$ ratio is known to be low in local ULIRGs (Figure 1, and Gracia-Carpio et al. 2011), likely due to a high ionization parameter. But in a few high-z high-$L_{\text{IR}}$ galaxies, $[\text{C II}]$ is strong, indicating different physical conditions. However, even with Herschel these lines are difficult to measure at high $z$ except in a small number of lensed or very luminous galaxies. To find local analogs, I selected non-merger disk galaxies from IRAS + SDSS, requiring near-ULIRG $L_{\text{IR}}$, large optical diameter, and non-AGN line ratios. These are rare ($\sim 6\%$) since most high $L_{\text{IR}}$ galaxies are mergers. I am obtaining Herschel/PACS spectra of $[\text{C II}]$ and $[\text{O I}]$ in 16 disk galaxies at $z \sim 0.1$. Results so far are shown in Figure 1.

We find that the $[\text{C II}]/L_{\text{IR}}$ ratio is indeed higher in the disky galaxies than in most local ULIRGs. The high-$L_{\text{IR}}$ disk sample (blue stars in Figure 1) bridges the gap between lower-luminosity local galaxies and high-$z$ galaxies with high $[\text{C II}]$, supporting the idea that evolution in the IR spectra is related to physical properties of star forming regions, and likely driven by global galaxy structure. It is suggestive of the idea that the Kennicutt-Schmidt relation is offset between disks and mergers (e.g. Genzel et al 2010), although whether the K-S relation is truly bimodal is highly controversial.

This sample shows both the promise of far-IR spectroscopy and the utility of large surveys to find connections between low and high-redshift objects. In the near future of this project we will compare line fluxes to models of PDRs and H II regions to constrain physical properties, and are taking longslit spectra to measure the distribution of star formation and extinction in the disks, and will propose for CO observations to measure gas mass and Kennicutt-Schmidt relations. In the longer term, between the Herschel archive, EVLA imaging, and ALMA spectroscopy, it will be possible to study the dependence of star formation on galaxy properties in much more detail. In the CCAT era sub-mm surveys and spectroscopy will yield much larger samples to study dust and gas in both low and high redshift galaxies.

2. Star formation rates in galaxy surveys: a HST survey for $\text{H} \alpha$ at $0.7 < z < 1.5$

I am leading a program with the WFC3/IR instrument, installed in Hubble Space Telescope in 2009, to carry out a slitless spectroscopic survey of most of the GOODS-N deep survey field, detecting $\text{H} \alpha$, the most sensitive star formation indicator, at $0.7 < z < 1.5$ (Cycle 17, 56 orbits, program GO-11600). We are measuring redshifts and $\text{H} \alpha$ fluxes for $\sim 500$ galaxies. I am also analyzing WFC3/IR grism data taken as part of supernova followup in the CANDELS multi-cycle HST IR survey, for which I am the grism science working group leader, and in the 3D-HST Treasury public survey (PI P. van Dokkum) which covers several fields to the depth of our GOODS-N survey.

Slitless spectroscopy and the high spatial resolution of HST allow a blind survey, measuring $\text{H} \alpha$ fluxes and the spatial extent of $\text{H} \alpha$ within galaxies; slitless IR spectroscopy is only practical from space with its lower thermal background. The blind survey and accurate HST fluxes are useful for interpreting samples that will be observed from the ground with forthcoming multi-object IR spectrographs and eventually spatially-resolved studies with JWST or AO on 30-m telescopes. These data will also be useful as a pathfinder for dark energy surveys: dark energy satellite designs, including Euclid and WFIRST, use IR slitless spectroscopy from space to perform similar blind redshift surveys for $\text{H} \alpha$, over much larger areas.

This project builds on work with Kai Noeske and members of the DEEP2 team, studying the evolution of the star formation rate as a function of stellar mass (Noeske et al. 2007). We used a combination of Spitzer far-IR and DEEP2 $[\text{O II}]$ emission lines to show that the $\sim 10\times$ decline of the global SFR with time (e.g. Lilly et al. 1996) is a gradual decline across the blue galaxy population, rather than being driven by a decrease in a high-SFR merger event rate.

Beyond the global SFR evolution, what we don’t know nearly as well are the specifics. When the global SFR was 10x higher, was it very high in a fraction of galaxies (e.g. mergers) or higher across the board? Is star formation more dust-obscured at high $z$? Is star formation concentrated in central starbursts, or distributed throughout galactic disks? Do metallicity and extinction throw
off SFR calibrations, e.g. through offsets to nebular line ratios, changes in the nebular or UV extinctions, or changes in the far-IR dust SED? The relations between SFR tracers are fairly well studied locally (e.g. Kennicutt 1998; Calzetti et al. 2007), but at \( z \gtrsim 0.5 \) scatter between SFR indicators is an inconvenience often swept under the rug. The scatter may average out for the global rate, but makes study of galaxy properties difficult.

The scatter between SFR indicators makes it difficult to study the properties of subtypes of galaxies, or evolution in e.g. dust content or metallicity effects. At \( z = 1 \), SFRs from [O II], assuming a mass-dependent extinction correction, and from 24 \( \mu \text{m} \) both show a strong mean trend with mass (Weiner et al. 2007). But the scatter in each is such that the two SFR measures are barely correlated. Metallicity and extinction can affect [O II] oppositely from far-IR, and uncertainties in their evolution feed into the black-box nature of high-\( z \) SFR measurements (Kewley et al. 2004). We don’t presently know if the scatter between SFR indicators can be explained by simple underlying physical properties of the galaxies, e.g. variations in the extinction or in the size and temperature of the star-forming regions.

Our survey addresses these questions by detecting H\( \alpha \), the most sensitive SFR tracer, down to SFR \( \sim 3M_\odot \text{yr}^{-1} \), for comparison with existing Spitzer far-IR, UV data, and optical ground-based spectroscopy of [O II], H\( \beta \), and other lines (existing and our follow-up of detected sources). Figure 2 shows an initial result: SFR from H\( \alpha \) fluxes and from far-IR agree fairly well. However, even though H\( \alpha \) and [O II] are roughly correlated, selecting on [O II] yields a highly biased result since [O II]/H\( \alpha \) is anti-correlated with far-IR.

Ground-based surveys for H\( \alpha \) at \( z \sim 1 \) have been difficult since IR spectroscopy of faint objects through the atmosphere is hard and slow. Furthermore, it is difficult to get accurate fluxes from the ground because slit losses are hard to quantify (e.g. Erb et al. 2006). The HST/WFC3-IR survey provides accurate H\( \alpha \) fluxes, and also can measure sizes of the galaxies in H\( \alpha \) emission. The sizes will enable us to study nuclear starbursts or bulge formation versus star formation in disks, and provide surface densities of star formation for comparison with the Kennicutt relation. The Kennicutt relation between SFR and gas surface densities will become especially interesting as existing mm-wave interferometers and ALMA, are now able to detect CO emission and measure the gas masses of star forming galaxies at \( z \sim 1 \) (Tacconi et al. 2010). Analysis of the WFC3-IR surveys will yield a great deal of information and point the way to spatially resolved studies with GSMT+AO and JWST. The low-resolution HST spectroscopy complements IR spectroscopy from the ground that can follow up selected objects at higher resolution, for example to resolve H\( \alpha \) and N\( \text{II} \) for metallicity and AGN studies.

3. Clustering of infrared-luminous galaxies

In another project to study the nature of star-formation and related AGN events at \( z \sim 1 \), I am working with Alison Coil to measure the clustering of IR-luminous galaxies, using redshifts from the DEEP2 survey and Spitzer/MIPS far-IR data in two of the DEEP2 fields. Clustering measurements are valuable because the evolution of clustering of dark matter halos is governed by gravitation, its physics well understood analytically and from simulations, and more massive halos are more strongly clustered. We can use the clustering strength of a galaxy type to link it to its present environment and its descendants: a strongly clustered population will live in denser environments and evolve into a strongly clustered present-day population.

Locally, IR-luminous galaxies are rare objects that are almost always major mergers of gas-rich massive galaxies, and will produce elliptical galaxies. ULIRGs are often thought to be a stage in a merger-ULIRG-QSO-elliptical progression (e.g. Sanders et al. 1988; Hopkins et al. 2006). However, it is not clear whether LIRGs at \( z = 1 \) are also mergers and interactions, or whether many of them are simply gas-rich spirals: Milky Way-type progenitors with a 5 – 10× higher SFR (e.g. Hammer et al. 2005 vs. Melbourne et al. 2005). Our goal is to distinguish these possibilities by studying their clustering and local environment: the progenitors of ellipticals should be more clustered than
those of spirals.

IR-luminous galaxies are rare enough that their clustering is noisy. We overcome this problem by computing their cross-correlation with redshifts of thousands of normal galaxies from the DEEP2 survey. Combining our MIPS observations with DEEP2 and followup spectra from MMT/Hectospec, we still have < 200 ULIRGs, so we measure the signal by cross-correlating the ULIRGs with the whole galaxy population, an approach used to measure QSO clustering by Coil et al. (2006).

We find that ULIRGs are as strongly clustered as red galaxies, but do not have an unusually large $r_0$. These are likely to evolve into the red galaxies that live in group environments today. ULIRGs are actually more clustered than the QSOs measured by Coil et al. (2006), suggesting the merger-ULIRG-QSO model is oversimplified. Meanwhile, bright LIRGs are clustered like the blue-galaxy population; the $z \sim 1$ LIRGs are more like spirals than like $z = 0$ LIRGs. More work is needed to model the clustering strengths, e.g. with halo occupation distribution models. We also plan to extend these studies with larger Spitzer surveys such as the MAGES Legacy survey of the 9 deg$^2$ Bootes field (on which I am deputy PI), and by cross-correlating SDSS and SDSS-3 samples with the all-sky IR survey of the WISE satellite. Further gains could be made at $z < 0.6$ with spectroscopic followup of WISE 23 µm sources and eventually all-sky spectroscopic surveys such as BigBOSS.

4. Star formation driven outflows at $z > 1$

Galactic winds and outflows driven by AGN or high surface densities of star formation are seen in the local universe in rare objects such as dwarf starbursts, and ULIRGs (Rupke et al. 2005; Martin 2005). Outflows in the early universe are a prime suspect for the enrichment of the IGM, and may cause metal-line QSO absorption systems spatially associated with galaxies. The mass-metallicity relation suggests that winds have ejected metals from low-mass galaxies, but does not tell us whether $L^*$ galaxies drove outflows in the past (Tremonti et al. 2004). High-SFR galaxies are much more common at $z > 1$, and in a composite spectrum of $z \sim 3$ Lyman-break galaxies, Shapley et al. (2003) detected outflows in blueshifted ISM absorption lines. These are likely progenitors of ellipticals, leaving open whether a galaxy like the Milky Way drove a wind in its past.

We used composite spectra of 1406 galaxies at the $z \sim 1.4$ high-redshift end of DEEP2, where [O II] provides the systemic redshift and Mg II 2796,2803 Å enters the spectrum, to show that blueshifted Mg II ISM absorption is ubiquitous in these blue-sequence starforming galaxies, the progenitors of today’s $L^*$ spirals (Figure 3; Weiner et al. 2009). The outflow occurs in galaxies over a range of 10× in SFR and 30× in stellar mass, and is stronger and larger in higher-mass, higher SFR galaxies. The velocity dependence helps to constrain models of wind physics used in cosmological simulations of mass-metallicity evolution (Finlator & Davé 2008).

I have worked with recent UCSC graduate Kate Rubin to extend similar studies to lower redshift (Rubin et al. 2010), and with Alison Coil, using UV spectra from Keck/LRIS-B to search for outflows from SDSS and DEEP2 post-starburst galaxies and weak AGN (Coil et al. 2011) to test outflow “quenching” models of star formation truncation by AGN. High velocity outflows have been seen in luminous post-QSO objects (Tremonti et al. 2007), but we found only lower-velocity outflows consistent with star formation driving, suggesting that AGN outflows are not directly responsible for quenching the post-starbursts. We also have an approved program for up to 3000 ancillary targets in SDSS3/BOSS, which is targeting galaxies near lines of sight to SDSS QSOs, to study the frequency of Mg II absorption systems and links to the properties of the associated galaxies, e.g. mass, SFR, and environment.
Figure 1: log $L([C\,\text{II}])/L_{IR}$ ratio as a function of far-IR luminosity $L_{IR}$. Blue stars are the 4 disky U/LIRGs observed so far in our Herschel program. Local data are from ISO on star-forming galaxies and LIRGs (black circles) and ULIRGs (red squares) (Malhotra et al 2001; Luhman et al 2003). Xes are upper limits. High-z galaxies (green circles) are lensed extreme star-forming galaxies from sub-mm telescopes and Herschel (Maiolino et al 2009; Hailey-Dunsheath et al 2010; Ivison et al 2010). The [C II]/FIR ratio declines with $L_{IR}$, due to changing physical conditions in the star-forming regions. Local ULIRGs studied so far are concentrated mergers with high surface brightness that may not be a good analog for high-z ULIRGs. The extreme high-z galaxies show higher [C II]/FIR than local galaxies of similar luminosity, possibly because their star formation is distributed over a larger area. Our disky U/LIRG sample fills a gap at high [C II] and $L_{IR}$, and makes good analogs for the high-z galaxies, confirming the hypothesis that IR surface brightness and physical conditions in the SF regions are linked.

References:


Figure 2: **Left panel:** Comparison of SFR from Hα and far-IR at 0.7 < z < 1.5. SFR(Hα) is from our WFC3-IR grism survey in GOODS-N and far-IR is from Spitzer/MIPS 24 μm. A constant extinction correction of 3.3× is applied to Hα (based on lower redshift Hα/Hβ) and works fairly well – Hα is a good tracer even in IR-luminous galaxies. The brightest galaxy in the plot is nearly a ULIRG (SFR=100, L_{IR} = 10^{12}). **Right panel:** Line luminosities, L([O II]) from ground-based Keck spectra vs. L(Hα) from WFC3-IR. Red points are the galaxies detected by MIPS 24 μm; these are presumably more obscured and strongly star-forming. Although Hα and [O II] are correlated, there are clearly biases introduced if L([O II]) is used as a SFR indicator. The MIPS-detected galaxies are at low [O II]/Hα, and selecting galaxies on [O II] tends to find galaxies with high [O II]/Hα, which are probably elevated in [O II] due to low metallicity and low extinction. This explains why [O II] and far-IR do not agree on a galaxy-by-galaxy basis. UV light is expected to have similar biases. Hα improves the situation by acting as a bridge between indicators.

Figure 3: Stacked spectra of 1406 galaxies from DEEP2 at z ∼ 1.4, where Mg II 2800 Å enters the DEEP2 spectral range (from Weiner et al. 2009). These are blue starforming galaxies with SFR ranging from 10-100 M⊙ yr⁻¹, including the ancestors of present-day L* galaxies. The vertical lines indicate the systemic velocity as measured by [O II] nebular emission. There is a strong blueshifted outflow signature in the Mg I and Mg II lines, which probe cool, neutral or low-ionization gas. These outflows are global, covering ∼ 50% of the z = 1.4 galaxy light. The outflows are stronger/faster in more massive, higher SFR galaxies (Weiner et al. 2009), which will help to constrain models for wind-driven outflows, their effects on galaxy evolution and metallicity, and IGM enrichment (Finlator & Davé 2007). We are now extending this study to lower redshift (Rubin et al. 2010) and to specific classes of objects (e.g. post-starbursts).