PROJECT DESCRIPTION

Understanding the formation and evolution of galaxies ranks as one of the most ambitious and important scientific goals of the astronomical community. The 2010 decadal panel report *New Worlds, New Horizons in Astronomy and Astrophysics* (National Research Council, 2010), which recommends funding priorities for NASA, NSF, and DOE, headlined their section on galaxy evolution studies with a direct question that is arguably the most important to be answered for understanding galaxies: "How do baryons cycle in and out of galaxies and what do they do while they are there?" The supporting text in the report highlights the methodology to tackle this question: "To probe baryons when they are in and around and between galaxies, one can use absorption spectra of background sources along lines of sight passing near galaxies. Such techniques probe both the gas distribution and its velocity field and will yield insights into gas accretion, outflows, chemical enrichment, and the overall cycle of matter between galaxies and the intergalactic medium (IGM). **Theoretical simulations will be critical for connecting such one-dimensional probes to the three-dimensional gas distribution**." (emphasis added)

There is tremendous historical context for the power of hydrodynamic cosmological simulation and absorption line analysis. The Ly α forest (the intergalactic medium, IGM) was scrutinized for 20 years before fundamental understanding of its topographical cosmic-web structure was achieved. The key step was comparison of real-world observational absorption lines to simulated absorption lines from the simulations (pioneered by Dave et al., 1997). Understanding galaxies is far more complex than was envisioned in the 1990s. It is now clear that accurately modeling the baryon cycle (the conversion of gas to stars and stars back into gas) is required to form realistic simulated galaxies (e.g., Ceverino & Klypin, 2009; Trujillo-Gomez et al., 2013). *It is important that successfully simulating a universe of galaxies that match observables is highly sensitive to the gas physics of the baryon cycle, for it means that observational constraints obtained from the gas properties provides tremendous leverage for forwarding our detailed understanding of how galaxies form and evolve.*

Realistic analysis of the absorption properties of simulated galaxies is a developing, but not mature research direction. As with the revolutionary understanding of the Ly α forest in the 1990s, the method holds tremendous potential for interpreting the observational data in the context of the topographical distribution, dynamics, chemical enrichment, ionization phases, and baryon cycle physics and for yielding giant leaps of insight into galaxy evolution theory. *No concentrated effort has yet been undertaken to realistically quantify absorption line analysis of the baryon cycle and the circumgalactic medium (CGM) in simulations with the goal of repeating the brilliant successes obtained with the* Ly α *forest.* **We propose** to pursue such an undertaking and to directly address questions central to understanding (1) the role of the the baryon cycle through the CGM, (2) the response of the CGM and baryon cycle to different feedback models, and (3) the implications for our understanding of galaxy evolution. Our target questions include:

1. How do the absorption properties of the CGM (i.e., the metallicity and kinematic and ionization conditions) evolved across the epoch of peak star formation in the universe for different feedback models for different mass galaxies?
2. Which feedback models are most consistent with both the observed properties of galaxies and the observe properties of the CGM?
3. How do galaxies of different masses accrete gas from the IGM, and how do different feedback models modify the accretion and transport of accreting gas through the CGM?
4. What are the mechanisms by which baryons are transported and cycled back into the CGM following stellar feedback processes, and how does that change with feedback recipe?
5. To what degree (quantified) do the gas properties we derive from commonly employed observational analysis techniques applied to absorption lines from simulations match the properties of the absorbing gas? Can we find systematic discrepancies and develop methods to calibrate standard analysis techniques?
6. Regarding all of the above, what are the implications for galaxy evolution?

1 THE IMPORTANCE OF THE BARYON CYCLE AND THE CGM

The totality of our working picture of the baryon cycle, including detailed insights into the properties, dynamics, and role of CGM in galaxy evolution, is derived by tracking the gas cycles and the modeling of star formation and feedback physics in simulations (e.g., Birnboim & Dekel, 2003; Kereš et al., 2005; Oppenheimer & Davé, 2008; Dekel & Birnboim, 2006; Kereš et al., 2009; Ceverino & Klypin, 2009; Fumagalli et al., 2011; van de Voort et al., 2011; Ceverino et al., 2014; Trujillo-Gomez et al., 2013). In fact, to understand the stellar-mass metallicity correlations, the flow and recycling of interstellar medium (ISM) and IGM gas through the CGM must be finely tuned to precise relative proportions. Davé et al. (2011a) showed that CGM gas content is regulated by a competition between IGM inflow and gas consumption within the ISM as governed by the star formation law. Star-forming galaxies develop via a slowly evolving equilibrium balanced by inflows (driven by gravity/mass), wind recycling, star formation rates, and outflows, the latter regulating the fraction of inflow that gets converted into stars (Davé et al., 2011b). Such work goes far to also explain the stellar-mass to halo-mass (SM/HM) relation (e.g., Behroozi et al., 2010, 2013), which peaks at 3% for $\simeq 10^{12}$ $M_{\odot}$ halos and declines toward both lower and higher halo masses. The astonishingly inefficient conversion of baryons to stars in galaxies and the halo mass dependence of this efficiency likely has its origins in the halo mass dependent large scale physics of the CGM.

The observed SM/HM relation and the fundamental mass relation (FMR) of the ISM (Tremonti et al., 2004; Mannucci et al., 2010; Bothwell et al., 2013) further suggest that galaxy evolution is governed by the response of baryonic gas in the CGM to the halo mass in which a galaxy resides. The overall ISM/CGM/IGM cycle, and the physical state of the CGM, is in response to competition between the cooling and dynamical timescales of accretion (Birnboim & Dekel, 2003; Dekel & Birnboim, 2006), the efficiency at which gas is processed in galaxies (Davé et al., 2011b; Dayal, Ferrara, & Dunlop, 2013; Lilly et al., 2013), the timescales at which it is expelled back into and mixed into the CGM (Oppenheimer & Davé, 2008; Ceverino & Klypin, 2009; Fumagalli et al., 2011; Stewart et al., 2011a), and the star formation law and efficiency of stellar feedback (Trujillo-Gomez et al., 2013; Ceverino et al., 2014). Dayal, Ferrara, & Dunlop (2013) found that for more massive galaxies, ISM metal enrichment due to star formation is diluted by inflow of metal-poor IGM gas that yields a constant value of the ISM gas metallicity with SFR (thereby reproducing the flat portion of the FMR at high mass). A detailed halo mass dependent model of the gas flow budget by Lilly et al. (2013) indicates that the SM/HM relation established by baryonic processes within galaxies implies a significant fraction (40%) of baryons in the CGM have been processed through galaxies.

In broad terms, IGM accretion is divided into two modes (which likely bracket the real world behavior). The critical variable is halo mass (Birnboim & Dekel, 2003; Dekel & Birnboim, 2006; Kereš et al., 2005, 2009; van de Voort et al., 2011). "Hot-mode" shocked-heated accretion dominates in high mass halos, $M_{\rm h} \geq M_{\rm crit}$, where $\log M_{\rm crit}/M_{\odot} \simeq 12$ due to short dynamical times compared to the cooling time. The hot gas accretes into the CGM but not into the galaxy ISM. "Cold-mode" accretion dominates for $M_{\rm h} < M_{\rm crit}$, where the cooling time is shorter than the dynamical time; the cold gas accretes directly onto the galaxy and fuels star formation. Models in which cool dense ($n_{\rm H} \simeq 10^{-1}$ cm^{-3}) clouds condense out of the hot CGM constrain the cool cloud masses to a narrow range ($\simeq 10^{5}$ M$_{\odot}$) due to competing destruction mechanisms (Kelvin-Helmholtz, evaporation, etc) and Jeans instabilities; the range narrows rapidly with increasing $\log M_{\rm h}/M_{\odot}$. Above $\log M_{\rm h}/M_{\odot} \simeq 12$, the allowed range vanishes and no cool clouds are predicted (Maller & Bullock, 2004; Stewart et al., 2011a).

Departures from these predictions would suggest that not all high mass halos have a hydrostatic hot CGM and/or the hot gas in low mass galaxies may have other origins than winds (for example, conductive interfaces of infalling cool clouds would have narrower kinematics characterized by multiple velocity components that trace the low ionization kinematics). Since hot mode accretion does not fuel star formation and therefore can partly explain the declining SM/HM ratio with increasing mass for $\log M_{\rm h}/M_{\odot} > 12$, if this mode is not confirmed observationally, it removes this theoretical construct as an explanation for the SM/HM relation at high halo mass.

1.1 Observations and Observational Analysis

Absorption lines sensitively record the kinematics, ionization balance, chemical content, densities, and temperatures of galactic baryons. Through absorption line analysis of absorption strengths, covering fractions, and velocity spreads CGM properties are characterized to high redshift. As shown in **Figure 1(a)**, Churchill et al. (2013a) showed that, in a given impact parameter range, D, higher mass halos have stronger Mg II absorption (a 4.1σ result). As shown in **Figure 1(b)**, when impact parameter is normalized by the virial radius, $R_{\rm vir}$, the mass segregation vanishes, indicating that the cool/warm CGM of galaxies is self-similar with absorption strengths that scale with $(D/R_{\rm vir})^{-2}$. The masses of the sample range from $10.5 \leq M_{\rm h}/M_{\odot} \leq 13.8$. These results indicate that the cool/warm CGM is ubiquitous, that the cycling of baryons between the ISM and the IGM is an active process regardless of galaxy mass, and that the CGM scales up with halo mass. This result places tension on the theoretical predictions of cloud survivability and the suppression of cold accretion for $\log M_{\rm h}/M_{\odot} > 12$.

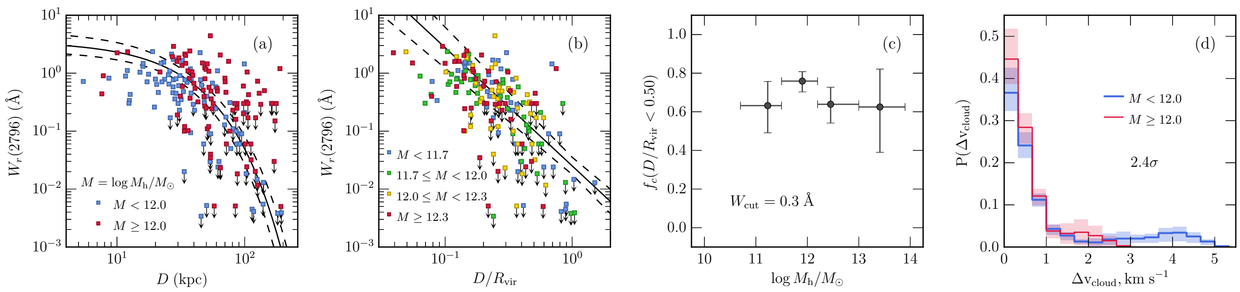

Figure 1. – **Observations Placing Tension on Theory** – (a) Mg II rest-frame equivalent width, $W_r(2796)$ as a function of impact parameter, showing that higher mass halos have stronger absorption strengths in fixed impact parameter ranges. (b) $W_r(2796)$ versus $D/R_{\rm vir}$, where $R_{\rm vir}$ is the virial radius, showing that the CGM is self-similar with halo mass. (c) The covering fraction within $D/R_{\rm vir} = 0.5$ for $W_r(2796) \geq 0.3$ Å absorption as a function of halo mass, showing that the covering fraction is independent of halo mass. (d) The velocity dispersion normalized to circular velocity of the Mg II absorbing CGM for high mass and low mass halos. For all panels, the range of halo mass of the sample is $10.5 \leq \log M_{\rm h}/M_{\odot} \leq 13.8$.

Further tension with theory is presented in **Figure 1(c)**, where the covering fraction of Mg II absorption with rest-frame equivalent widths greater than 0.3 Å is shown to be flat with halo mass (Churchill et al., 2013a). This shows that cold mode accretion cannot be consistent with the observed CGM, since it predicts that the covering fraction vanishes for $M_{\rm h}/M_{\odot} > 12$. Thus the cool/warm CGM in high mass halos must be sustained by winds, or the absorption is due to tidal streams such as the LMC/SMC stream around the Milky Way.

Theory has not yet addressed predictions of the kinematics of the CGM with respect to host galaxies. However, it might naively be expected that higher mass galaxies have higher velocity dispersion in their CGM. Higher velocity dispersion would result in CGM gas that is less able to settle into the ISM and fuel star formation, which would be consistent with the declining SM/HM relation toward higher masses. In **Figure 1(d)**, we present unpublished results of the pixel two-point velocity correlation function for Mg II absorbing gas around low and high mass halos. The velocities are normalized to the host galaxy circular velocities in order to remove mass scaling. Note that higher mass halos are characterized by a CGM with lower velocity dispersion around the host galaxy (only a 2.4σ significance). As such, it would appear that the observed kinematics do not support the notion that cool/warm gas is dynamically suppressed from accreting into galaxies embedded in higher mass halos. *Comparing these types of results to simulations will provide insights into the tension they create with theoretical expectations.*

At $z \sim 0.1$, the CGM may harbor a reservoir of chemically enriched gas with a mass rivaling the gas reservoir in galaxies (Tumlinson et al., 2011, 2013; Stocke et al., 2013). Most CGM gas appears have velocity spreads of $\simeq 250$ km s^{-1} and remains bound within the host galaxy halo. Gas giving rise to O VI absorption ($n_{\rm H} \simeq 10^{-4}$ cm^{-3}, $T \sim 3 \times 10^5$ K) is ubiquitous around high specific star forming galaxies out to $D \simeq 150$ kpc. A cool/warm CGM phase ($n_{\rm H} \simeq 10^{-1}$ cm^{-3}, $T \sim 3 \times 10^4$ K), observed with Mg II absorption, is also ubiquitous. At $z \sim 0.5$, cool/warm gas is observed out to $D \sim 150$ kpc with a covering fraction of 70% (Nielsen et al., 2013b). Kinematically, both winds (Tremonti et al., 2007; Martin & Bouché, 2009; Weiner et al., 2009; Rubin et al., 2010; Martin et al., 2012) and infalling gas (Rubin et al., 2011; Kacprzak et al., 2010a; Kacprzak et al., 2012b) is detected. Similar to the hot O VI absorbing phase at $z \sim 0.1$, the velocity spreads of Mg II absorbing gas are on the order of $\simeq 250$ km s^{-1} and most of the gas remains bound within the host galaxy halo (Nielsen et al., 2014). Using H I absorption selection, Lehner et al. (2013) found that the CGM gas metallicity was bimodal, from which they deduced the higher metallicity gas has likely been processed through the galaxy ISM and injected to the CGM via stellar winds, whereas the lower metallicity gas is less processed infalling IGM or mixed recycled material. Cold accretion and galactic outflow components of the CGM may have geometric preferences about galaxies. Cool metal-poor H I infall preferentially occurs in the plane of the galaxies (Kacprzak et al., 2010a, 2011b; Rubin et al., 2011), consistent with simulations of cold accretion (Stewart et al., 2011b). Winds exhibit opening angles of $\sim 50^\circ$ about the galaxy minor axis out to 40–50 kpc (Bordoloi et al., 2011; Kacprzak, Churchill, & Nielsen, 2012a; Bordoloi et al., 2012).

For CGM studies, the redshift range from $1 \leq z \leq 2$ is known as the "redshift desert" because of the difficulty in identifying and obtaining galaxy redshifts across this cosmic epoch. However, at $z \sim 2.5$, the Keck Baryon Structure Survey (KBSS Steidel et al., 2010; Rakic et al., 2012; Rudie et al., 2012; Trainor & Steidel, 2012) reveals the CGM as a conductive interface between the large scale cosmic web and the feedback processes within galaxies. At this higher redshift, the CGM blends into the IGM at roughly 300 kpc (proper) from galaxies. It has been claimed that the CGM does not evolve from $0 \leq z \leq 2.2$ in that the spatial extent and mean absorption equivalent width of the CGM around galaxies of comparable mass have changed little over this cosmic time interval (Chen, 2012). However, this is doubtful. First, the data are drawn from a heterogeneous sample of low-resolution observations compiled from the literature. Second, the CGM responds to the UV background (UVB) radiation spectral energy distribution (Haardt & Madau, 2011), which evolves in step with the luminosity density of quasars and the global star formation density. Third, the fact that the star formation density peaks toward later redshifts for dwarf galaxies and at higher redshifts for massive galaxies (Behroozi et al., 2013) is a strong indication of CGM evolution that is galaxy halo mass dependent. In fact, Matejek et al. (2012) show that the rise and fall in the cosmic number density of strong Mg II absorbers out to $z = 5$ mirrors that of the cosmic star formation rate density, suggesting the CGM traces galactic outflows or other byproducts of star formation.

2 HYDRODYNAMICS IN COSMOLOGICAL SIMULATIONS

In general, there are two main approaches to simulating galaxies and the CGM. The first uses smoothed particles hydrodynamics (SPH), which discretizes gas mass into particles, and the second uses adaptive mesh refinement (AMR), which spatially discretizes the gas using grid cells. SPH simulations generally trade off high spatial and mass resolution in favor of modeling the hydrodynamics in thousands of galaxies in a simulation box. With SPH simulations the statistical characteristics of the CGM can be studied over a wide range of halo mass and cosmological environment.

With AMR simulations, star formation and feedback models directly target the underlying physical processes of star formation and feedback. Though the processes are spatially unresolved, the physics is highly detailed and can be employed to study star formation at the scale of molecular cloud physics and stellar feedback at the scale of radiation pressure physics and photoheating physics. With AMR, greater insight into the baryon cycle, and therefore galaxy formation and evolution theory, is gleaned.

2.1 Feedback: The Physics of the Baryon Cycle

Traditionally, the term stellar feedback has been synonymous with supernovae (SNe) feedback. However, SNe are not the dominant process at early times around massive stars; a combination of photoionization and radiation pressure drive the dynamics of the star forming region and provide ∼200 times the mechanical energy of SNe II or stellar winds.

2.1.1 Old Approaches to Supernovae and Winds (SNW)

SNe feedback prevents excessive conversion of baryons into stars (Dekel & Silk, 1986). Early simulations were limited by low resolution so that SNe were modeled too simplistically (Navarro & Benz, 1991; Katz et al., 1992; Navarro & White, 1993; Navarro & Steinmetz, 2000; Abadi et al., 2003). To form galaxies with realistic SM/HM ratios, several ad-hoc methods were introduced, including (1) a modified effective equation of state (Springel & Hernquist, 2003; Teyssier et al., 2010), (2) artificially preventing gas cooling immediately after injecting thermal energy (Gerritsen & Icke, 1997; Thacker & Couchman, 2000; Sommer-Larsen et al., 2003; Kereš et al., 2005; Governato et al., 2007; Agertz et al., 2011), (3) storing feedback energy in an unresolved, hot reservoir of gas (Scannapieco et al., 2008), or (4) imposing galactic winds that scale directly with global galaxy properties and may or may not respond hydrodynamically (Springel & Hernquist, 2003; Dalla Vecchia & Schaye, 2008; Oppenheimer & Davé, 2008; Schaye et al., 2010; Dalla Vecchia & Schaye, 2012; Vogelsberger et al., 2013). However, these methods had two major shortcomings: not being physical, they are unable to investigate the role of the baryon cycle in governing galaxy evolution, and they fail to reproduce the low rates of stellar mass growth of galaxies at $z < 1$ (Trujillo-Gomez et al., 2013, and references therein).

2.1.2 New Approaches to Radiation Pressure (RP) and Photoheating (PH)

Several studies have concluded that the combination of radiation pressure and photoheating of gas by massive stars is the dominant mechanism for disrupting molecular clouds and regulating the star formation process (e.g., Krumholz & Matzner, 2009; Indebetouw et al., 2009; Murray & Rahman, 2010; Andrews & Thompson, 2011; Lopez et al., 2011; Pellegrini et al., 2011; Hopkins et al., 2011; Krumholz & Thompson, 2012). Photoionization heating is the main driver of gas expansion in H II regions (Lopez et al., 2014). That is, momentum and energy injection from radiation disrupts molecular clouds long before the first SNe explosions (Kawamura et al., 2009).

The treatment of momentum (i.e., nonthermal) pressure in fully cosmological simulations is new (Hopkins et al., 2014; Agertz et al., 2013; Trujillo-Gomez et al., 2013; Ceverino et al., 2014). More commonly, thermal energy from massive stars is injected into the gas (similar to SNe thermal feedback, Brook et al., 2011; Macciò et al., 2012; Schaye et al., 2014), or kinetic energy is imparted while temporarily decoupling the gas from hydrodynamic forces (e.g., Genel et al., 2012; Vogelsberger et al., 2013). Injecting a thermal component does not capture the baryon cycle physics nor does it regulate star formation, as is possible with radiative feedback (Hopkins et al., 2011; Trujillo-Gomez et al., 2013; Ceverino et al., 2014). The new paradigm of galaxy formation is one in which radiation from massive stars is responsible for regulating star formation and powering galactic winds, while the properties of the ISM are controlled by the energy from SNe.

2.2 Our Simulations

We perform our simulations using the adaptive mesh refinement N-body and hydrodynamics code hydroART (Kravtsov et al., 1997; Kravtsov & Klypin, 1999). This code is adaptive in both space and time allowing it to achieve higher resolution in high density regions.

Physical processes implemented in the code include star formation, stellar feedback, Type II and Ia metal enrichment, thermal and radiation pressure, and metallicity-dependent cooling and heating. Gas is self-shielded, advects metals, is heated by a homogeneous ultraviolet background, and can cool to 300 K due to metal and molecular line cooling. Gas flows, shock fronts, and metal disbursement follow self-consistently from this physics. We use observations of molecular clouds (Krumholz & Tan, 2007) to guide our model of star formation. Star formation occurs in the dense, cold molecular phase ($n_{\rm H} \sim 100$ cm^{-3}, $T \simeq 100$ K), which is disrupted by the combination of radiation pressure and photoionization by massive stars (Trujillo-Gomez et al., 2013). The star formation rate is proportional to the gas density divided by the free fall time of the molecular cloud. We use an observationally motivated low (few percent) efficiency per free fall time for converting gas into stars. Runaway young, hot stars are included according to Ceverino & Klypin (2009) by providing one third of the newly-formed star particles with a random velocity kick.

The resolution ranges from 20–200 pc, depending on redshift. Each gas cell stores the hydrogen density, $n_{\rm H}$, temperature, T, and metal mass fraction, Z. We developed a full-treatment photo+collisional ionization code (Churchill et al., 2014, fully tested against Ferland's Cloudy) that computes the ionization corrections for all ionic species in each cell of the simulation box. The code accounts for shielding by neighboring cells and for both UVB and stellar radiation (using Starburt99 SEDs accounting for the distribution, ages, and metallicities of stellar particles).

2.2.1 Our Approach to Baryon Cycle Physics

In addition to SNe Type Ia and II explosions, we have incorporated photoionization heating, radiation pressure, and shocked stellar winds from massive stars into our version of hydroART (see Ceverino & Klypin, 2009; Ceverino et al., 2010; Trujillo-Gomez et al., 2013; Ceverino et al., 2014, for details). The inclusion of the dynamical effect of photoionization heating is unique to our version of hydroART. We implement it by adding a non-thermal pressure ($P/k = x \times 10^6$ K cm^{-3}, where $1 \leq x \leq 50$) to the gas surrounding young stars, matching observations of H II regions (Lopez et al., 2014). This pressure decreases rapidly in order to reproduce the declining density within a growing H II region. Concurrently, mechanical energy from stellar winds and SN type II is assumed to thermalize and is injected into the gas as thermal energy around young stars following the rates predicted by Starburst99 (Leitherer et al., 1999) for the Chabrier IMF.

Similar to Murray & Rahman (2010), (Hopkins et al., 2011), and Agertz et al. (2013), we include radiation pressure from young massive stars due to momentum from the radiation field, which couples to the gas and dust through scattering and absorption. Absorption of UV photons scales as $1 - e^{-\tau_{\rm UV}} \simeq 1$. Scattering due to trapped IR photon scales as $\tau_{\rm IR} \simeq 1$. Though Murray & Rahman (2010) and Hopkins et al. (2011) suggest $\tau_{\rm IR} \sim 50$–100, lower values of $\tau_{\rm IR} \sim 1$–10 are favored (Krumholz & Thompson, 2012) in which $\tau_{\rm IR}$ scales with column density (Davis et al., 2014).

2.2.2 Successes with This Feedback Model

In Ceverino et al. (2014) and Trujillo-Gomez et al. (2013) we find that the radiative feedback maintains an extended galaxy with a rising circular velocity profile. The main effect of radiation pressure is to regulate and limit the high values of gas density and the amount of gas available for star formation. We find that the fraction of cold baryons within the simulated dwarf galaxies is 20–30%, in agreement with THINGS. Unlike SNe energy, radiation from massive stars reduces the central density of the dark matter halo of a galaxy with $M_* \sim 10^8 M_\odot$, in support of recent observations. We find in Trujillo-Gomez et al. (2011) that the standard cosmological model, used in conjunction with halo abundance matching and simple dynamical corrections, fits all basic statistics of galaxies with circular velocities $V_{\rm circ} > 80$ km s^{-1}. Our primary observational constraints are the SH/HM ratios and the luminosity-velocity relation which generalizes the Tully-Fisher and Faber-Jackson relations in allowing all types of galaxies to be included, and provides a fundamental benchmark to be reproduced by any theory of galaxy formation.

3 CONFRONTING AND INTERPRETING OBSERVATIONS FROM THEORY

In order for observational absorption line studies to have meaningful impact on our understanding of the baryon cycle and its role in galaxy evolution, the results deduced from these studies must accurately reflect the reality of the universe. However, there are many explicit and implied assumptions that are applied to observational absorption line analysis and we remain blind to knowing how they may systematically skew our understanding of the baryon cycle.

For example, ionization models (e.g., Cloudy, Ferland et al., 1998; Ferland et al., 2013) are used to determine the gas density, $n_{\rm H}$, metallicity, physical depth, and mass. Explicit assumptions include employing single-phase absorbing clouds (e.g., Lehner et al., 2013; Stocke et al., 2013; Werk et al., 2014), or simple two-phase absorbing clouds (e.g., Charlton et al., 1999; Churchill & Charlton, 1999; Charlton et al., 2003; Ding et al., 2003b; Tripp et al., 2011; Kacprzak et al., 2012b). How appropriate are these assumptions as revealed by the absorbing gas structures in the simulations? When modeling two-phase structure, how does one partition the observed H I absorption between the two phases when only line of sight velocity information is recorded? This is critical to get correct because the ionization corrections and inferred metallicity (and mass) of the gas will be totally inaccurate unless the adopted H I fractions of the phases are correct. Quantifying the relationships between absorption profiles, the inferred properties of the absorbing gas from the absorption line data, and the "true" properties of the gas giving rise to the absorption in the simulations can provide insight to these questions.

A second example is the inferred kinematics, which is either assumed to be provided by the profile of the column density with velocity via the apparent optical depth (AOD) column density method (e.g., Savage & Sembach, 1991), or reflected in Voigt profile (VP) decomposition of the absorption profile (e.g., Churchill, Vogt, & Charlton, 2003; Simcoe et al., 2006, and many others). However, inferring the kinematic properties of the gas using either the AOD profile method and VP decomposition implicitly relies on the assumption that gas at a given velocity arises from a single unique spatial location along the line of sight. Furthermore, VP decomposition models the data as isothermal clouds, each having a different line-of-sight peculiar velocity. Using simulations, the relative spatial locations of the absorbing gas along the LOS can be examined to quantify the degree to which absorption with similar (or aligned) kinematics arises in the same spatial gas structures. This latter information also has important implications for the assumptions applied to the ionization modeling and kinematic analysis of observed data.

Absorption line analysis simulations should emulate published absorption-line surveys. Only in this way is the gas studied in absorption in the simulations quantitatively selected in the identical fashion as the gas studied in observational spectra. The importance of this cannot be overstated. **Direct insight from simulations can be gleaned only if the gas being compared to observations can be isolated in the simulations**. For example, the instrument/telescope used to observe a given absorption line depends upon the rest wavelength of the transition and the redshift of the absorber. The range of physical gas properties that contribute to detectable absorption will differ as a function of the detection threshold of the spectra, which depends on the signal-to-noise ratio, resolution, and pixelization of the data. Shallower detection thresholds result in studying gas with higher column densities, which presumably means higher density, higher metallicity gas, or favorable ionization conditions. This holds true for both real-world observations and synthetic spectra from simulations.

3.1 Methods

First, the ionization model (Churchill et al., 2014) is run on the simulation box, from which the number densities of all ions are determined for each gas cell. To generate "observed" quasar spectra, a line of sight (LOS) is passed through the simulation box from the vantage point of an "observer" viewing the galaxy on the plane of the sky. Each LOS is defined by (1) an impact parameter, D, (2) a position angle on the plane of the sky, Φ, which ranges from $\Phi = 0^\circ$ to 360°, and (3) the inclination, i, of the simulated galaxy with respect to the LOS direction.

The orientation of the galaxy in the simulation box is defined by the angular momentum vector of the star particles. Once D, Φ, and i are specified, we determine the direction cosines (ℓ, m, n) of the LOS with respect to the box coordinate system. For an individual simulated galaxy, we can create and study an arbitrary number of randomly oriented or parallel LOS. This formalism allows the opportunity study the relationship between galaxy orientation and absorption line properties (e.g., Bordoloi et al., 2011; Bouché et al., 2012; Kacprzak, Churchill, & Nielsen, 2012a). Typically, we run 1000 LOS through the simulated galaxy for four to five galaxy orientations. The LOS range from $0 \leq D/R_{\rm vir} \leq 2.0$. For comparison with observations, the synthetic spectra are generated using the exact characteristics of observed data, including the resolution (convolution with the instrumental spread function), pixelization, and noise characteristics. As illustrated in **Figure 2**, the spatial and dynamics state of the gas can be compared to the absorption profiles for direct insight into the physical location as a function of absorption velocity. Successive time steps provide the history of the CGM gas, and we can examine evolution from $z = 5$ (or higher) to $z = 0$.

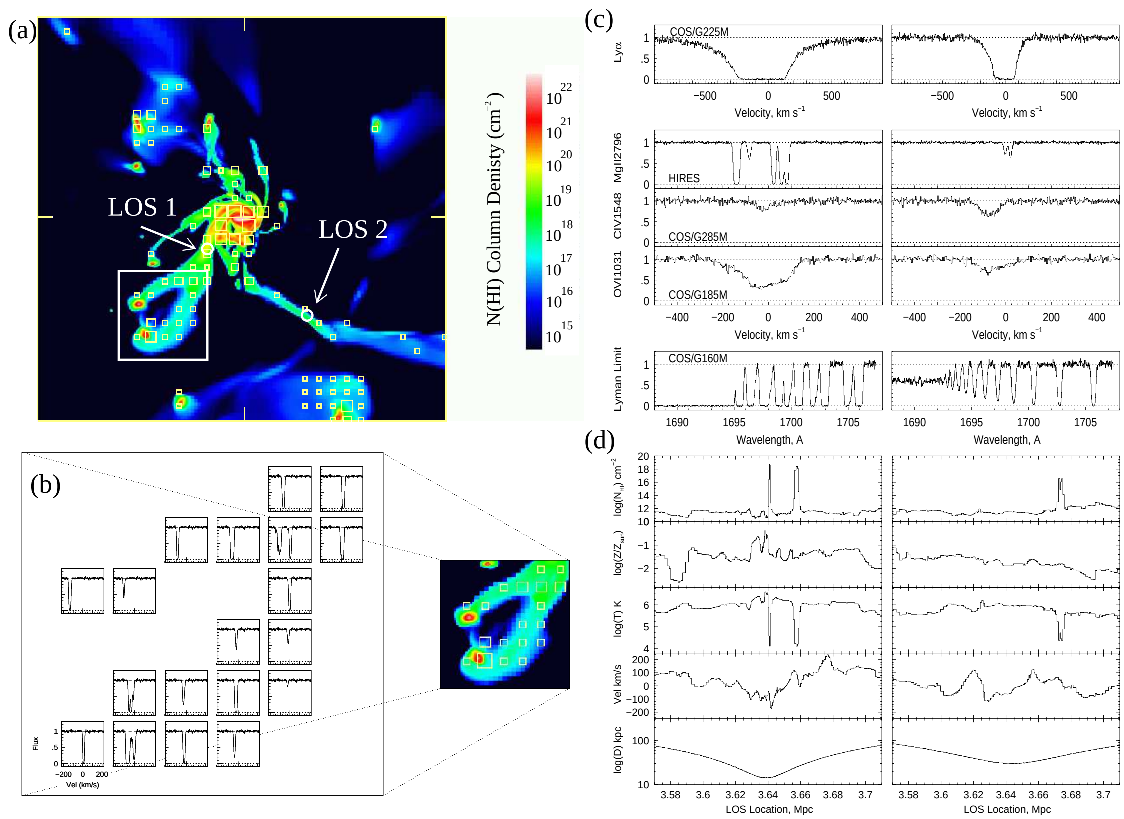

Figure 2. – **Absorption Lines through Simulations** – (a) Lines of sight through a $z = 0.9$ simulated galaxy showing locations of detected Mg II absorption (open squares) to a 0.02 Å threshold in "HIRES" spectra (Kacprzak et al., 2010a). The image is 170×170 kpc. The color scale provides integrated $N(\text{H I})$. (b) "HIRES" Mg II absorption lines probing a filament region (boxed in panel a). (c, left) "HIRES" and "COS" Lyα, Mg II, C IV, O VI, and Lyman Limit (LL) absorption through a region with $\log N(\text{H I}) = 19.8$ (LOS 1, panel a). (c, right) LOS 2 absorption through a region with $\log N(\text{H I}) = 16.9$. (d) The gas $N(\text{H I})$, metallicity $[Z/Z_\odot]$, density n_H, line of sight velocity, and galactocentric distance D, as a function of the line of sight position.

To study the gas cells responsible for detected absorption for a given transition/ion, the cells with LOS velocities aligned within the objectively defined velocity range of the absorption profiles are sorted into ascending column density order. We iteratively regenerate synthetic spectra with the same instrumental characteristics and detection sensitivities for the transition while progressively omitting one gas cell at a time until the equivalent width of the profile changes by 5%.

We have fully developed and tested a science-ready pipeline to (1) generate LOS vectors, (2) run the LOS through the simulations, (3) generate realistic simulated spectra with fully specified data characteristics, (4) automatically and objectively detect and quantitatively measure the absorption lines, and (5) determine the gas cells in the simulations that give rise to the detected absorption lines for each ion for each LOS, and (6) catalog the results for science analysis. Details are presented in Churchill et al. (2014). We have also developed analysis software that computes commonly employed quantities such as covering fractions, equivalent width and column density distributions, etc., and generates many of the standard plots in the published literature for direct comparison with observations.

Analysis from the simulations will mirror observations (such as those described in Section 1.1) and all analysis will follow the standard practices employed in these observational works, including ionization modeling (described further below). *The true uniqueness of our method is that the synthetic absorption line data will be measured and modeled identically as the observed*

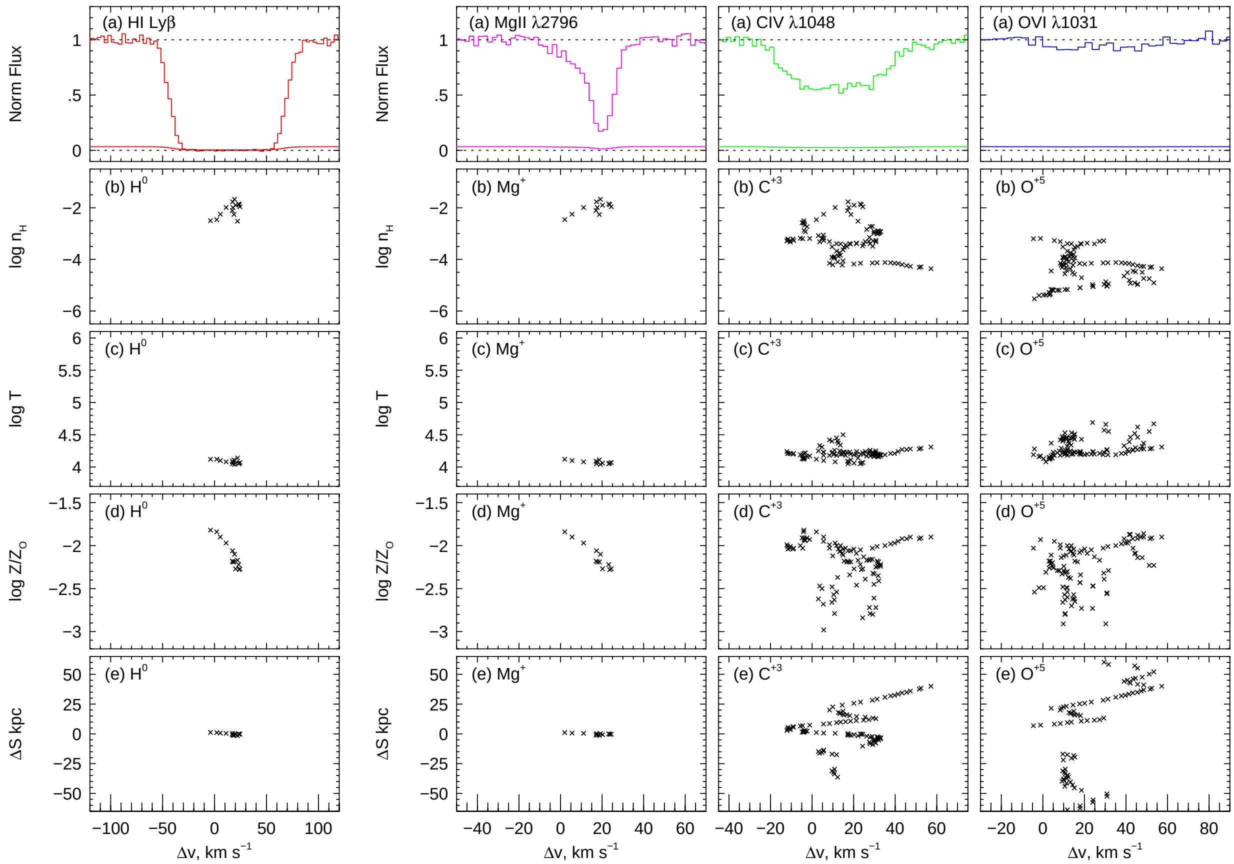

Figure 3. – Phase, Abundance, Spatial, and Kinematics of Absorbing Gas– All quantities plotted as a function of LOS velocity for an example LOS. (a) The Lyα, Mg II, C IV, and O VI synthetic absorption profiles. (b) The absorbing cell hydrogen number densities, $n_{\rm H}$. (c) The absorbing cell temperatures, T. (d) The absorbing cell metallicities, $\log Z/Z_{\odot}$. (e) The absorbing cell LOS positions, ΔS.

data, including the detection threshold sensitivity. Thus, we will be able to study the simulated gas structures that are selected by absorption using the same data characteristics of the observations.

For the ionization modeling, Co-PI Charlton has written an iterative script that drives the ionization code, CLOUDY (Ferland et al., 1998; Ferland et al., 2013). We consult with Gary Ferland (U. Kentucky) for challenging models and when problems arise. Our default ionizing continuum SED is the UV background of Haardt & Madau (1996, 2011); however, we systematically superimpose various stellar contributions to examine plausible variations in deduced cloud properties. The input for the script is the list of VP cloud column densities, b parameters, and velocities. This provides an initial kinematic-column density "template" for a system, which is incorporated into a model by segregating low ionization gas and high ionization gas kinematics using the template methods developed by Co-PI Charlton (Charlton et al., 1999; Churchill & Charlton, 1999; Charlton et al., 2003; Ding et al., 2003a,b, 2005). The method has been applied successfully to account for up to four individual gas phases. The script iteratively runs CLOUDY, solves for the column densities and b parameters for all transitions, and generates synthetic spectra that are χ^2 minimized to the data. For each of the absorber component, we constrain the metallicity, the density, temperature, turbulent component, and ionization parameter. We also consider adjustments from solar abundance pattern when required by the data.

3.2 First Insights from our Pilot Study

In Figure 3(a) plot the synthetic absorption profiles from the simulations of Trujillo-Gomez et al. (2013) from the work of Churchill et al. (2014). In panels (b), (c), (d), and (e) we plot the absorbing cell hydrogen number densities, $n_{\rm H}$, temperatures, T, metallicities $Z/Z_{\odot}$ (in solar units), and LOS position ΔS (where $\Delta S = 0$ is the plane of the sky, $\Delta S < 0$ is the toward the observer, and $\Delta S > 0$ is toward the background source) as a function of LOS velocity Δv (where $\Delta v = 0$ is the galaxy systemic velocity).

These results clearly show that certain assumption underlying standard observational absorption line analysis methods are not validated for all ions. The H I absorption and the Mg II absorption is distributed over a range of velocities in gas that forms a single contiguous structure at $\Delta S \simeq 0$ (i.e., a single "cloud"). However, at most LOS velocities, the C IV and O VI absorbing gas originates from multiple groupings of cells with physical separations ranging from a 10 to 50 kpc. Consider the velocity $\Delta v \simeq 15$ km s^{-1}, where the C IV absorption at this velocity arises in six distinct structures along the LOS and the O VI absorption arises in five distinct structures! These structures are physically distributed over a spatial range of ~ 50 kpc, but each structure is on the order of a few kiloparsec in size. Clearly, the common assumption of absorption at fixed velocity arising in a single structure is invalidated for C IV and O VI absorbing gas.

In Churchill et al. (2014), we concluded that current observational analysis techniques are likely to be valid for low-ionization gas. The H I and Mg II absorption arise in a single contiguous gas structures with a narrow range of temperature and hydrogen density. However, often half-dex or so metallicity gradients are present (see **Figure 3(d)** for H I and Mg II), indicating that single values of metallicity are likely to be invalid. Standard observational techniques and Cloudy modeling applied to COS spectra by Werk et al. (2014, $L \sim L^{*}$ galaxies) and Stocke et al. (2013, $L > 0.1L^{*}$ galaxies) constrained the properties of the cool/warm photoionized CGM to reside near the values shown here. However, analysis of O VI absorbers that leads to conclusions such as "kinematical correlation of the cold and warm-hot phases indicates that the warm-hot plasma is related to the interaction of the cold matter with a hotter (unseen) phase. Such multiphase winds can remove substantial masses and alter the evolution of post-starburst galaxies" (Tripp et al., 2011) could potentially be grossly incorrect. In the example shown, there is kinematic alignment of the H I and Mg II absorption with the O VI absorpion, but *none* of the O VI arises in the same gas as the H I and O VI and they are not interfacing with one another. Further analysis of the simulation data will go far to examine whether we, as a community, are making correct statements about the baryon cycle and it's role in evolution.

4 RESEARCH PLAN

We aim to undertake a comprehensive quantitative analysis of the simulated CGM, comparing the inferences derived from various observational works to the inferences derived from the application of observational analysis methods to simulated absorption data. Examples of observational data that can be compared are the published covering fractions, the column density and equivalent width impact parameter distributions, and the kinematics. These quantities will provide insight into how the CGM properties reflect different stellar feedback models by comparing the absorption properties to observations and finding the closest match with the real world. Central to our goals is that we will employ *absorption selected* gas properties to quantify the degree to which the observational analysis methods accurately recover the "true" properties of absorbing gas. We aim to determined to what degree of accuracy the inferred densities, temperatures, and metallicities from observational modeling techniques are recovered when applied to the simulated spectra and compared to the simulation gas properties.

In Table 1, we present our library of completed, currently running, and proposed simulations. We target halos from the dark matter N-body runs and complete the hydrodynamics and galaxy formation within a cosmological context by zooming in on galaxies of specific $z = 0$ halo mass and cosmological environment. We focus on the central galaxies in the "field", but we emphasize that we obtain the full cosmological local environment of these galaxies, which includes a sum total of hundreds of small satellite halos with full hydrodynamic treatment, star formation, and stellar feedback. To date, we have run hydrodynamics on 37 unique central dark matter halos using two different star formation models and four different feedback models (see Section 2).

Table 1. Completed and Planned Simulations

Point Person[a]/ Model	Feedback Model[b]	Number of Galaxies	Gas Res [pc]	DM Res [$M_\odot$]	$\log M_{\rm h}(z)$ [$M_\odot$]	Status[d]
Milky Way Masses: Probabilistic Star Formation[c], Various Feedback						
DC/VELA1	SNW	35	17	8×10^4	11.0-12.3 (1)	done
DC/VELA2	SNW+RP	35	17	8×10^4	11.0-12.3 (1)	done
DC/VELA3	SNW+RP+PH1	35	17	8×10^4	11.0-12.3 (1)	running[e]
KA/VELA4	SNW+RP+PH2	10	17	8×10^4	11.0-12.3 (1)	started
Dwarf Galaxies: Deterministic Star Formation[c], Various Feedback						
ST/dwSN	SNW	1	40	9×10^4	10.5 (0)	analyzed
ST/dwRP$_1$	SNW+RP	1	40	9×10^4	10.5 (0)	done
ST/dwRP$_{10}$	SNW+RP	1	40	9×10^4	10.5 (0)	done
ST/dwRP$_{50}$	SNW+RP	1	40	9×10^4	10.5 (0)	done
ST/dwALL$_1$	SNW+RP+PH2	1	40	9×10^4	10.5 (0)	analyzed
ST/dwALL$_8$	SNW+RP+PH2	1	40	9×10^4	10.5 (0)	analyzed
ST/dwALL$_{40}$	SNW+RP+PH2	1	40	9×10^4	10.5 (0)	analyzed
Sub-Milky Way Mass: Deterministic Star Formation[c], Various Feedback						
ST/spSN	SNW	1	80	8×10^5	11.3 (0)	running[f]
ST/spALL$_8$	SNW+RP+PH2	1	80	8×10^5	11.3 (0)	done
ST/spALL$_{40}$	SNW+RP+PH2	1	80	8×10^5	11.3 (0)	done
NEW: Dwarf and Milky Way Masses: Deterministic Star Formation[c], Best Feedback						
KA/dwBEST[g]	SNW+RP+PH2	30	15	1×10^3	8.3-10.3 (0)	preparing
all/VELA5[h]	SNW+RP+PH2	30	20	8×10^4	10.3-12.5 (0)	preparing

(a) DC = Daniel Ceverino; KA = Kenza Arraki; ST = Sebastian Trujillo-Gomez; all = KA + ST + Glenn Kacprzak (GK). The subscript in the model name denotes a factor of x in the photoheating pressure term $P/k = x \times 10^6$ K cm^{-3}. (b) "SNW" = SNII and stellar winds; "RP" = radiation pressure; "PH1" = weak photoheating per Ceverino et al. (2014); "PH2" = moderate photoheating per Trujillo-Gomez et al. (2013). (c) Star formation: " Probabilistic" = per Ceverino et al. (2014); "Determinstic" = per Trujillo-Gomez et al. (2013). (d) "done" = data cubes stored, ready for analysis; "started" = subset of galaxies is running; "analyzed" = gas and/or absorption line analysis highly progressed or complete. (e) currently at z = 2. (f) currently at z = 0.5. (g) "BEST" = SNW+RP+PH2 with "$x = 1$". (g) this proposal.

As of this writing, 35 '"Milky Way" mass galaxies (VELAs 1–4) have been run with "probabilistic" star formation, in which all the gas in a cell meeting the required density and temperature criterion is or is not fully converted to stars for a fixed probability (Ceverino et al., 2014). One dwarf galaxy and one sub-Milky Way mass galaxy have been run with "deterministic" star formation, in which 2% of the gas in a cell is converted to stars with unity probability (Trujillo-Gomez et al., 2013). The deterministic star formation and the feedback models that include supernovae+stellar wind (SNW), radiation pressure (RP), and moderate photoheating (PH2) produce the most realistic galaxies (Trujillo-Gomez et al., 2013), so we adopt these models (SNW+RP+PH2) for future simulations to compare against our existing simulations. We will run these additional galaxies over the first two years of the proposed research time line.

We are now finalizing the initial conditions for 60 additional central halo galaxies with mass range $8.3 \leq \log M_{\rm h}/M_\odot \leq 12.5$ (at $z = 0$). These simulations (identified as dwBEST and VELA5 in Table 1) will be run with high mass and spatial resolution (1×10^3 $M_\odot$ to 8×10^4 $M_\odot$ and 15–20 pc) allowing us to accurately capture the physical processes of star formation and stellar feedback. We estimate that evolving 60 central halo galaxies to $z = 0$ will take $\sim$10 mega-CPU hrs, which we have access to through the NASA Ames "Pleiades", NERSC "Hopper" supercomputer facilities, and (through collaborator Dr. Glenn Kacprzak) the "swinSTAR" supercomputers.

We will run all galaxies through our absorption line pipeline (1000 LOS for a given orientation through a given galaxy), generating absorption line profiles for H I Lyman series line, Mg II, C IV, O VI and several other commonly observed transition/ions (cf., **Figure 2**). We objectively identify the absorption and measure all quantities (i.e., equivalent widths, velocity widths, AOD column densities, etc.), and then we compare to the published distributions of these quantities (cf., **Figure 1**) from surveys such as MAGIICAT (Nielsen et al., 2013a,b; Churchill et al., 2013a,b), COS-Dwarfs (Bordoloi et al., 2014), COS-Halos (Tumlinson et al., 2011, 2013), our own Large *HST* program (Churchill, 2013), the Colorado Group's work (Stocke et al., 2013), and the Chicago Group's work (Chen et al., 2001a,b; Liang & Chen, 2014). For $z > 2$, we compare to the published works of the Keck Baryon Structure Survey (Steidel et al., 2010; Rakic et al., 2012; Rudie et al., 2012; Trainor & Steidel, 2012). In all cases we emulate the methods applied by the observers.

Using our technique to select out the gas cells responsible for absorption of each of the ions, we will directly examine the gas phases (density and temperature), metallicities, and spatial and kinematic relationships between absorption and the absorbing gas (as piloted in Churchill et al., 2014). Using the VELA 1–5 and dwarf galaxy simulations, we will cross compare the results for various star formation and feedback models.

Photoionization modeling is key to how we infer the gas properties from the absorption line date, so we will focus on this extensively. We will compare the deduced densities, metallicities, and temperatures from ionization modeling to the absorption selected gas cell properties and for the first time be able to examine the accuracy of ionization modeling of gas partaking in the baryon cycle. We will provide co-PI Charlton a few hundred simulated spectra for a range of LOS. She will then photoionization model them using standard methods, including single-phase and multi-phase Cloudy (Ferland et al., 1998; Ferland et al., 2013) modeling. This will be a blind experiment, for she will not know the properties of the gas in the simulations. We then can quantify the differences between the deduced properties from the models and the gas properties in the simulations. Co-I Charlton is developing new methods for modeling multi-phase absorption, and will use the simulation data to calibrate these methods.

4.1 Team and Division of Labor

PI Churchill will manage the project and collaborative efforts, direct and engage in the analysis, interpret results, and write scientific papers. He will mentor and guide the graduate students at NMSU. **Co-PI Klypin** will complete the initial conditions for the proposed simulations and manage the running of simulations by Ms. Kenza Arraki, and Dr. Sebastian Trujillo-Gomez. He will engage in interpreting results and writing papers. **Co-PI Charlton** will lead efforts to examine current photoionization modeling methods and to develop new methods that more accurately recover the gas properties in the simulations from absorption line data. She will also supervise the efforts of the PSU graduate student and engage in interpreting results and writing papers.

Graduate Students: Ms. Kenza Arraki (NMSU) is a primary coder and will be responsible for running the simulations at NASA/Ames and NERSC, managing their storage, and engaging in quality-check and preliminary analysis. Mr. Jacob Vander Vliet (NMSU) will run the absorption line pipeline and engage in comparing simulated absorption line properties to both published observational data and the simulated gas properties. Mr. Jackson Norris (PSU) will be running photoionization models in both observational data (archival HIRES and *HST* data; all in hand and in fully science-ready status), and simulated spectra. All three students already have extensive experience and require no learning/training period.

Collaborators: Dr. Sebastian Trujillo-Gomez (Zurich) is a primary coder and will be responsible for running the simulations, managing their storage, and engaging in quality-check and preliminary analysis. He is an expert at analyzing the simulations and will engage in quantifying the baryon flow for the star formation and feedback models. Dr. Glenn Kacprzak (Swinburne) will be responsible for running the simulations on Swinburne's "swinSTAR" supercomputer. He is an expert on the absorption line galaxy connection and will engage (with Mr. Vander Vliet) in analyzing and comparing the observed and simulated absorption line data in the context of the host galaxies. Both collaborators will engage in interpreting results and writing papers.

4.2 Science, Outcomes, and Legacy

Our work promises to provide quantitative insight into (1) the relationship between the baryon cycle and the resulting properties of galaxies for various star formation and feedback models, and (2) the relationship between the baryon gas properties as deduced from standard observational techniques and the actual gas properties giving rise to the absorption. We aim to carefully assess how current observational analysis methods can be evolved to provide improved accuracy in recovering the gas properties, which is critical for constraining galaxy evolution theory since these observed quantities provide the data that simulations must strive to reproduce (if the deduced properties are incorrect they are misleading theory). We anticipate that three graduate students will complete their Ph.D. dissertations as a result of the proposed research and funding. We also anticipate that the collaborator postdocs will substantially advance their young careers.

We aim to publish two to three papers a year. We will begin by publishing comparison with observational data for the existing VELA and dwarf galaxies, followed by comparisons between the deduced gas properties and the actual gas properties, highlighting quantified insights into the misapplied assumption employed in current observational methods (see Churchill et al., 2014). We will then publish suggested improvements in the photoionization modeling methods and analysis methods. As the new proposed simulations are added, we will then compare stellar formation and feedback models and publish analysis of the baryon cycle response to these differing models, including the implications for our understanding of galaxy evolution.

Our work with the simulations, because it is unique in the manner in which we carefully (1) conduct our analysis to emulate real-world observations, (2) select the gas giving rise to absorption lines, and (3) use fully tested star formation and feedback models that are highly detailed, physically motivated, and on the cutting edge of present day understanding, promises to significantly contribute to our understanding of the baryon cycle, galaxy evolution, and how observational absorption line analysis techniques can be improved to better constrain galaxy evolution theory.

5 HUMAN RESOURCE DEVELOPMENT

PI Churchill has worked with eight successful NMSU undergraduate students including four minority females who are first generation college students. One was a McNair scholar. Two are still working with him, and three have gone on to graduate school and/or bridge to doctoral programs in astronomy. Since 2008, Churchill graduated five Ph.D. students; one a professor (Hofstra University), one an Australian Futures Fellow (Swinburne), one an Outreach Astronomer at STScI, one a Planetarium Director at a Museum, and one an Economic Programmer (Nashville). Churchill has graduated three M.S. students, now working as data analysts in astronomy. Since 2008, his students have authored or co-author 19 journal papers (one has 12 papers!). Churchill currently has four graduate (one 1st year, two 4th years, and one 5th year) and one undergraduate student actively involved in research. The present proposal will support three of these graduate students toward their PhDs. All students will contribute to NMSU outreach events.

Co-PI Klypin has graduated four highly successful Ph.D. students. Two are professors at graduate level institutes and two are postdocs (Madrid and Zurich). Most notably, Klypin mentored Dr. Andrei Kravtsov (University of Chicago). Klypin has graduated two M.S. students; both are successful in industry. Currently, Klypin is mentoring three graduate students. All students contribute to NMSU outreach events.

Co-PI Charlton maintained active Research Experiences for Undergraduates components with her previous NSF awards. A total of 29 undergraduate student have been supported. Among them, there are 13 published first-author and 40 co-authored journal papers. Most have gone to graduate school in astronomy and one is a JWST Project Scientist (NASA/Goddard). Four graduate students have been supported by Charlton's NSF funding for absorption lines; they are now an assistant professor, a Wall Street analyst, a professor in India, and a NASA postdoc. The present proposal will provide support for a graduate student who is starting his Ph.D. thesis on photoionization modeling of *HST*/COS absorbers. Charlton conducts supervised research with 2-3 undergraduate students each year. All students will contribute to Penn State outreach events.

6 SUMMARY OF PREVIOUS NSF SUPPORT

PI Churchill, was co-I on NSF grant AST-9617185, "The History of Galactic Gas at Redshifts 2.5 to 4" ($185K, 8/97-7/01). He was PI of NSF grant AST-0708210 ($286K, 9/07-8/11) entitled "Probing the Galaxy-Halo/Cosmic Web Interface and Galaxy Evolution." **Intellectual Merit:** A total of 20 refereed journal papers resulted from the 1997-2001 funding, and 9 papers from the 2007-2011 funding. At NMSU, the 2007-2011 funding supported four graduate students toward their successful PhDs. In addition to all the science directly accomplished due to this award, the funding set the stage for the highly successful Mg II-Absorber Galaxy Catalog (MAGIICAT: Nielsen et al., 2013a,b; Churchill et al., 2013a,b; Nielsen et al., 2014), and the successful Large Program *HST* program (110 orbits for COS quasar absorption spectra) by to our team (Churchill, 2013) to study the kinematics, spatial distribution, ionization conditions, and phases of the $z < 1$ CGM and compare them to galaxy morphologies, kinematics, metallicities and star formation rates. **Broader Impact:** PI Churchill proposed and developed a junior undergraduate level class (ASTR 308, "Into the Final Frontier"), designed to inspire and interface underrepresented students with the growing commercial space industry in Las Cruces and southern New Mexico. As proposed, he has incorporated class-led "interviews" with individuals outside academia, which provides students direct contact with potential future employers. He has forged strong connections with the Director of Personnel Relations (Maria Simpson, who took the class!) at Space Port America (located at one hour drive from Las Cruces). To date, she has hired two of Churchill's students and has interviewed several others for public relations positions for the Space Port.

Co-PI Klypin was PI of NSF grant AST-1009908 ($95K, 8/10-9/14) entitled "Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population." **Intellectual Merit:** Altogether, 23 refereed journal were published with a wide range of collaborators and students. With this funding, Co-PI Klypin studied the effects of stellar feedback on the formation and properties of forming galaxies in cosmological galaxy formation simulations. Details of many key science results (e.g., Trujillo-Gomez et al., 2011, 2013; Ceverino et al., 2014; Arraki et al., 2014), from this funding are a major component of the discussion in Section 2.2. **Broader Impact:** Klypin played a key role in providing community-wide access to the simulations through the "multidark.org" database, which reached hundreds of thousands of people.

Co-PI Charlton was PI of the NSF grant AST-0407138, "Quasar Absorption Lines: Probing Galactic Gas at Redshifts One to Two " ($252K, 8/02-7/09). Charlton was PI (Churchill as Co-I) on NSF grant AST-9617185, "The History of Galactic Gas at Redshifts 2.5 to 4" ($185K, 8/97-7/01). Charlton was PI for AST-0908984, "Exploring Compact Groups as a Laboratory for Morphological Transformations" ($200K, 8/09-7/12), AST-0807993, "Understanding Quasar Central Engines Using Narrow Intrinsic Absorption Lines" (co-I; $286K, 8/08-7/13), and AST-1313140 ($266K, 8/13-7/16), with the same title. **Intellectual Merit:** Charlton and Churchill (then at Penn State) publish 20 refereed papers in ApJ and AJ. With the latter awards, Charlton and her team published 18 additional refereed papers. **Broader Impact:** Charlton developed a science fiction, interactive, web astronomy version of the Penn State course Astro 001. This raised the astronomy enrollments by 50%, keeping Penn State in the lead nationally in astronomy credits taught to non-science students. Over 10,000 students have now taken Charlton's web course on campus, and more than 1000 more through Penn State's distance learning degree program, World Campus. The class receives excellent student reviews, and test scores are 5-10% higher than in her traditional lecture course.

7 BROADER IMPACT

PI Churchill consistently participates in and assists in organizing outreach activities, such as the monthly Open House hosted by the NMSU Astronomy Department. He gives public and private tours at the Apache Point Observatory, routinely speaks at elementary schools and STEM "Career Days" events, and volunteers each year for the eight-week Las Cruces After School Program, where he teaches space flight and/or astronomy to elementary school children. His NSF funded research is always a cornerstone subject for these opportunities. Broader impact for Churchill centers around Space Port America. Churchill will continue to participate in quarterly community outreach activities that include model rocket launching, tours, lectures about human space flight, and direct interaction with leaders in the local commercial space flight industry. Churchill proposes to continue to expand his previous NSF funded Broader Impact program, which centers around his course "Into the Final Frontier", in which careers of underrepresented students are promoted by connecting them with the local Space Port America aerospace/tourism industry. Roughly 45% of NMSU's student enrollment is Hispanic. He also works with the Space Port Director of Personnel Relations (Maria Simpson) to forge student opportunities. No NSF funding is requested for his continued efforts, since the pilot phase is now complete and the course and outreach connections are now self sustaining under the auspices of NMSU.

Co-PI Klypin has been a key player in providing community-wide access to our newest and best simulations through the "multidark.org" database (Riebe et al., 2013). On average, at any moment, $\sim$ 5–10 astronomers access the data for their research. The images and animations have been used by BBC, *Sky and Telescope*, and *National Geographic*. In 2011, *Sky and Telescope* featured our simulations on its front page. In the public show "Deep Space Adventure" at Adler Planetarium in Chicago, the show features computer animation of the formation of structures in the expanding Universe that was produced by our group. Hundreds of thousand people see the show every year. Our simulations have also reached the public through NASA, NBC, *Forbes Magazine*, the blog site *BoingBoing*, the *International Business Times*, *Science Daily*, and the Richard Dawkins Foundation (RichardDawkins.net). Klypin will continue these efforts.

Co-PI Charlton is a leader in astronomy outreach for Penn State Astronomy, which reaches some 10,000 K-12 students and the general public each year. Charlton and her students organize an annual Astrofest, a four-night festival of astronomy held during the town Arts Festival. Over 16 years, the event has reached more than 28,000 people! Charlton leads Astrofest and a number of other similar outreach events, participates in teacher workshops, and engages in K-12 programs. Charlton developed a science fiction, interactive, web astronomy version of Penn States Astro 001 course, raising enrollment by 50% and test scores by 5-10%. Now Charlton is adapting the Penn State web class to be a true, immersive, 3-D video game, teaching concepts through sub-games in the context of a story. This course was just successfully piloted at Penn State. We request some funding to support our effort to adapt this game to teach astronomy to middle school students through a month-long unit. We aim to exploit the enthusiasm young people devote to video games to achieve K–12 STEM standards for the state of Pennsylvania. We target the middle school level, but also address standards at higher/lower levels. Charlton's former undergraduate student, Nahks Tr'Ehnl, is working on the video game project. Tr'Ehnl has constructed an impressive Mars landscape, immersive planetarium, solar system model, and many other pieces of art. One of the many sub-games that has been developed conveys intuitive understanding of emission- and absorption-line spectra through students maneuvering atoms to reproduce spectra. We request modest travel support each year critical to support Tr'Ehnl's professional development through opportunities to present at professional conferences. Our specific plans involve alliances with teachers at two school districts (one in New Jersey and one in Pennsylvania) for pilot testing in year 1. We will recruit clients in other districts through our collaboration with Heather Nelson, the Assistant Director of the Pennsylvania Space Grant Consortium, who routinely works with a network of teachers state wide. Assessment will be handled by Dr. Chris Palma, who is an astronomy instructor at Penn State and expert on STEM education.

References

Abadi, M. G., Navarro, J. F., Steinmetz, M., & Eke, V. R. 2003, "Simulations of Galaxy Formation in a Cold Dark Matter Universe. I. Dynamical and Photometric Properties of a Simulated Disk Galaxy," ApJ, 591, 499

Agertz, O., Kravtsov, A. V., Leitner, S. N., & Gnedin, N. Y. 2013, "Toward a Complete Accounting of Energy and Momentum from Stellar Feedback in Galaxy Formation Simulations," ApJ, 770, 25

Agertz, O., Teyssier, R., & Moore, B. 2011, "The formation of disc galaxies in a ΛCDM universe," MNRAS, 410, 1391

Andrews, B. H., & Thompson, T. A. 2011, "Assessing Radiation Pressure as a Feedback Mechanism in Star-forming Galaxies," ApJ, 727, 97

Arraki, K. S., Klypin, A., More, S., & Trujillo-Gomez, S. 2014, "Effects of baryon removal on the structure of dwarf spheroidal galaxies," MNRAS, 438, 1466

Behroozi, P. S., Conroy, C., & Wechsler, R. H. 2010, "A Comprehensive Analysis of Uncertainties Affecting the Stellar Mass-Halo Mass Relation for $0 < z < 4$," ApJ, 717, 379

Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, "The Average Star Formation Histories of Galaxies in Dark Matter Halos from $z = 0$–8," ApJ, 770, 57

Birnboim, Y., & Dekel, A. 2003, "Virial Shocks in Galactic Haloes?," MNRAS, 345, 349

Bordoloi, R., Lilly, S. J., Knobel, C., Bolzonella, M., Kampczyk, P., Carollo, C. M., Iovino, A., Zucca, E., Contini, T., Kneib, J., Le Fevre, O., Mainieri, V., Renzini, A., Scodeggio, M., Zamorani, G., Balestra, I., Bardelli, S., Bongiorno, A., Caputi, K., Cucciati, O., de la Torre, S., de Ravel, L., Garilli, B., Kovac, K., Lamareille, F., Le Borgne, J., Le Brun, V., Maier, C., Mignoli, M., Pello, R., Peng, Y., Perez Montero, E., Presotto, V., Scarlata, C., Silverman, J., Tanaka, M., Tasca, L., Tresse, L., Vergani, D., Barnes, L., Cappi, A., Cimatti, A., Coppa, G., Diener, C., Franzetti, P., Koekemoer, A., Lopez-Sanjuan, C., McCracken, H. J., Moresco, M., Nair, P., Oesch, P., Pozzetti, L., & Welikala, N. 2011, "The Radial and Azimuthal Profiles of Mg II Absorption around $0.5 < z < 0.9$ zCOSMOS Galaxies of Different Colors, Masses and Environments," MNRAS, 743, 10

Bordoloi, R., Lilly, S. J., Kacprzak, G. G., & Churchill, C. W. 2012, "Modeling the Distribution of Mg II Absorbers Around Galaxies using Background Galaxies and Quasars," arXiv:1121.3774

Bordoloi, R., Tumlinson, J., Werk, J. K., Oppenheimer, B. D., Peeples, M. S., Prochaska, J. X., Tripp, T., M., Katz, N., Davé, R., Fox, A., Thom, C., Ford, A. B., Weinberg, D. H., Burchett, J. N., & Kollmeier, J. A. 2014, "The COS-Dwarfs Survey: The Carbon Reservoir Around sub-L* Galaxies," arXiv:1406.0509

Bothwell, M. S., Maiolino, R., Kennicutt, R., Cresci, G., Mannucci, F., Marconi, A., & Cicone, C. 2013, "A Fundamental Relation between the Metallicity, Gas Content and Stellar Mass of Local Galaxies," MNRAS, 433, 1425

Bouché, N., Hohensee, W., Vargas, R., Kacprzak, G. G., Martin, C. L., Cooke, J.& Churchill, C. W. 2012, "Physical Properties of Galactic Winds using Background Quasars," MNRAS, 426, 801

Brook, C. B., Governato, F., Roškar, R., Sinson, G., Brooks, A. M., Wadsley, J., Quinn, T. Gibson, B. K., Snaith, O., Pilkington, K., House, E., & Pontzen, A. 2011, "Hierarchical formation of bulgeless galaxies: why outflows have low angular momentum," MNRAS, 415, 1051

Ceverino, D., Dekel, A., & Bournaud, F. 2010, “High-redshift clumpy discs and bulges in cosmological simulations,” MNRAS, 404, 2151

Ceverino, D., Dekel, A., Tweed, D., & Primack, J. 2014, “Early formation of massive, compact, spheroidal galaxies with classical profiles by violent disc instability or mergers,” arXiv:1409.2622

Ceverino, D., & Klypin, A. 2009, “The Role of Stellar Feedback in the Formation of Galaxies,” ApJ, 695, 292

Ceverino, D., Klypin, A., Klimek, E., Trullio-Gomez, S., Churchill, C. W., & Primak, J. 2013, “Radiative Feedback and the Low Efficiency of Galaxy Formation in Low-Mass Halos at High Redshift,” MNRAS, 442, 1545

Charlton, J. C., Ding, J., Zonak, S., Churchill, C. W., Rigby, J. R., & Bond, N. A. 2003, “High-Resolution STIS/Hubble Space Telescope and HIRES/Keck Spectra of Three Weak Mg II Absorbers toward PG 1634+706,” ApJ, 589, 111

Charlton, J. C., Mellon, R. R., Rigby, J. R., & Churchill, C. W. 1999, “Predicting High–Resolution STIS Spectra of Four Multi-Phase Mg II Absorbers: A Test of Photoionization Models,” ApJ, 545, 635

Chen, H.-W. 2012, “The Unchanging Circumgalactic Medium Over the Past 11 Billion Years,” MNRAS, 427, 1238

Chen, H.-W., Lanzetta, K. M., & Webb, J. K. 2001a, “The Origin of C IV Absorption Systems at Redshifts $z < 1$: Discovery of Extended C IV Envelopes around Galaxies,” ApJ, 556, 158

Chen, H.-W., Lanzetta, K. M., Webb, J. K., & Barcons, X. 2001b, “The Gaseous Extent of Galaxies and the Origin of Ly Absorption Systems. V. Optical and Near-Infrared Photometry of Lyα-absorbing Galaxies at $z < 1$,” ApJ, 559, 654

Churchill, C. 2013, “A Breakaway from Incremental Science: Full Characterization of the $z < 1$ CGM and Testing Galaxy Evolution Theory’,’ *HST* Proposal, 13398

Churchill, C. W. & Charlton, J. C. 1999, “The Multiple Phases of Intermediate/Halo Gas in a Possible Group of Galaxies at z 1,” AJ, 118, 59

Churchill, C. W., Klimek, E., Medina, A., & Vander Vliet, J. R. 2014, arXiv:1409.0916

Churchill, C. W., Nielsen, N. M., Kacprzak, G. G., & Trujillo-Gomez, S. 2013a, “The Self-similarity of the Circumgalactic Medium with Galaxy Virial Mass: Implications for Cold-mode Accretion,” ApJ, 763, L42

Churchill, C. W., Trujillo-Gomez, S Nielsen, N. M., & Kacprzak, G. G. 2013b, “MAGIICAT III. Interpreting the Self-Similarity of the Circumgalactic Medium with Virial Mass Using Mg II Absorption,” ApJ, 777, in press (Dec. 2013)

Churchill, C. W., Vander Vliet, J. R., Trujillo-Gomez, S., Kacprzak, G. G., & Klypin, A. 2014, “Direct Insights into Observational Absorption Line Analysis Methods of the Circumgalactic Medium Using Cosmological Simulations,” arXiv:1409.0914

Churchill, C. W., Vogt, S. S., & Charlton, J. C. 2003, “The Physical Conditions of Intermediate-Redshift Mg II Absorbing Clouds from Voigt Profile Analysis,” AJ, 125, 98

Dalla Vecchia, C., & Schaye, J. 2008, “Simulating galactic outflows with kinetic supernova feedback,” MNRAS, 387, 1431

Dalla Vecchia, C., & Schaye, J. 2012, "Simulating galactic outflows with thermal supernova feedback," MNRAS, 426, 140

Dave, R., Hernquist, L., Weinberg, D. H., & Katz, N. 1997, "Voigt-Profile Analysis of the Lyα Forest in a Cold Dark Matter Universe," ApJ, 477, 21

Davé, R., Oppenheimer, B. D., & Finlator, K. 2011, "Galaxy Evolution in Cosmological Simulations with Outflows II. Metallicities and Gas Fractions," MNRAS, 415, 11

Davé, R., Oppenheimer, B. D., & Finlator, K. 2011b, "Galaxy Evolution in Cosmological Simulations with Outflows I. Stellar Masses and Star Formation Rates," MNRAS, 415, 11

Davis, S. W., Jiang, Y.-F., Stone, J. M., & Murray, N. 2014, "Radiation Feedback in ULIRGS: Are Photons Movers and Shakers?," arXiv:1403.1874

Dayal, P., Ferrara, A., & Dunlop, J. S. 2013, "The Physics of the Fundamental Metallicity Relation," MNRAS, 430, 2891

Dekel, A., & Birnboim, Y. 2006, "Galaxy bimodality due to cold flows and shock heating," MNRAS, 368, 2

Dekel, A., & Silk, J. 1986, "The origin of dwarf galaxies, cold dark matter, and biased galaxy formation," ApJ, 303, 39

Ding, J., Charlton, J. C., & Churchill, C. W. 2005, "The Absorption Signature of Six Mg II-selected Systems over $0.5 < z < 0.9$," ApJ, 621, 615

Ding, J., Charlton, J. C., Bond, N. A., Zonak, S. G., & Churchill, C. W. 2003, "A Quadruple-Phase Strong Mg II Absorber at $z \sim 0.9902$ toward PG 1634+706," ApJ, 587, 551

Ding, J., Charlton, J. C., Churchill, C. W., & Palma, C. 2003b, "The Multi-Phase Absorption Systems toward PG 1206+459," ApJ, 590, 746

Ferland, G., Korista, K. T., Verner, D. A.,Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, "CLOUDY 90: Numerical Simulation of Plasmas and Their Spectra," PASP, 110, 761

Ferland, G. J., Porter, R. L., van Hoof, P. A. M., Willaims, R. J. R., Abel, N. P., Lykins, M. L., Shaw, G., Henney, W. J., & Stancil, P. C. 2013, "The 2013 Release of Cloudy," RMxAA, 49, 137

Fumagalli, M., Prochaska, J. X., Kasen, D., Dekel, A., Ceverino, D., Primack, J. R. 2011, "Absorption-line Systems in Simulated Galaxies Fed by Cold Streams," MNRAS, 418, 1796

Genel, S., Naab, T., Genzel, R., Förster Schreiber, N. M., Sterberg, A., Oser, L., Johansson, P. H., Davé, R., Oppenheimer, B. D., Burkert, A. 2012, "Short-lived Star-forming Giant Clumps in Cosmological Simulations of $z \simeq 2$ Disks," ApJ, 745, 11

Gerritsen, J. P. E., & Icke, V. 1997, "Star formation in N-body simulations. I. The impact of the stellar ultraviolet radiation on star formation," A&A, 325, 972

Governato, F., Willman, B., Mayer, L., et al. 2007, "Forming disc galaxies in ΛCDM simulations," MNRAS, 374, 1479

Haardt, F., & Madau, P. 1996, "Radiative Transfer in a Clumpy Universe. II. The Ultraviolet Extragalactic Background," ApJ, 461, 20

Haardt, F., & Madau, P. 2011, "Radiative Transfer in a Clumpy Universe. IV. The Ultraviolet Extragalactic Background," ApJ, 746, 125

Hopkins, P. F., Kereš, D., Oñorbe, J., Faucher-Giguère, C.-A., Quataert, E., Murray, N., & Bullock, J. S. 2014, "Galaxies on FIRE (Feedback In Realistic Environments): stellar feedback explains cosmologically inefficient star formation," MNRAS, 445, 581

Hopkins, P. F., Quataert, E., & Murray, N. 2011, "Self-regulated star formation in galaxies via momentum input from massive stars," MNRAS, 417, 950

Indebetouw, R., de Messières, G. E., Madden, S., Engelbracht, C., Smith, J. D., Meixner, M., Brandle, B., Smith, L. J., Boulanger, F., Galliano, F., Gordon, K., Hora, J. L., Sewilo, M., Tielens, A. G. G. M., Werner, M., & Wolfire, M. G. 2009, "Physical Conditions in the Ionized Gas of 30 Doradus," ApJ, 694, 84

Kacprzak, G. G., Churchill, C. W., Barton, E. J., & Cooke, J. 2011, "Halo Gas and Galaxy Disk Kinematics of a Volume-limited Sample of Mg II Absorption-selected Galaxies at $z \sim 0.1$," ApJ, 733, 105

Kacprzak, G. G., Churchill, C. W., Ceverino, D., Steidel, C. C ., Klypin, A., & Murphy, M. T. 2010a, "Halo Gas and Galaxy Disk Kinematics Derived from Observations and ΛCDM Simulations of Mg II Absorption Selected Galaxies at Intermediate Redshift," ApJ, 711, 533

Kacprzak, G. G., Churchill, C. W., & Nielsen, N. M. 2012a, "Tracing Outflows and Accretion: A Bimodal Azimuthal Dependence of Mg II Absorption ", ApJ, 760, L7

Kacprzak, G. G., Churchill, C. W., Steidel, C. C., Spitler, L. R., & Holtzman, J. A. 2012b, "Discovery of Multi-Phase Cold Accretion in a Massive Galaxy at $z = 0.7$," MNRAS, 427, 3029

Katz, N., Hernquist, L., & Weinberg, D. H. 1992, "Galaxies and gas in a cold dark matter universe," ApJ, 399, L109

Kawamura, A., Mizuno, Y., Minamidani, T., Filipović, M. D., Staveley-Smith, L., Kim, S., Mizuno, N., Onishi, T., Mizuno, A., & Fukui, Y. 2009, "The Second Survey of the Molecular Clouds in the Large Magellanic Cloud by NANTEN. II. Star Formation," ApJS, 184, 1

Kereš, D., Katz, N., Fardal, M., Davé, R., & Weinberg, D. H. 2009, "Galaxies in a simulated ΛCDM Universe I. Cold Mode and Hot Cores," MNRAS, 395, 160

Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, "How Do Galaxies Get Their Gas?," MNRAS, 363, 2

Kravtsov, A. V., & Klypin, A. A. 1999, "The Origin and Evolution of Halo Bias in Linear and Nonlinear Regimes," ApJ, 520, 437

Kravtsov, A. V., Klypin, A. A., & Khokhlov, A. M. 1997, "Adaptive Refinement Tree: A New High–Resolution N–Body Code for Cosmological Simulations," ApJS, 111, 73

Krumholz, M. R., & Matzner, C. D. 2009, "The Dynamics of Radiation-pressure-dominated H II Regions," ApJ, 703, 1352

Krumholz, M. R., & Tan, J. C. 2007, "Slow Star Formation in Dense Gas: Evidence and Implications," ApJ, 654, 304

Krumholz, M. R., & Thompson, T. A. 2012, "Direct Numerical Simulation of Radiation Pressure-driven Turbulence and Winds in Star Clusters and Galactic Disks," ApJ, 760, 155

Lehner, N., Howk, J. C., Tripp, T. M., Tumlinson, J., Prochaska, J. X., O'Meara, J. M., Thom, C. Werk, J. K., Fox, A. J., & Ribaudo, J. 2013, "The Bimodal Metallicity Distribution of the Cool Circumgalactic Medium at $z \leq 1$," ApJ, 770, 138

Leitherer, C., Schaerer, D., Goldader, J. D., Delgado, R., Robert, C., Kune, D. F., de Mello, D. F., Devost, D., & Heckman, T. M. 1999, "Starburst99: Synthesis Models for Galaxies with Active Star Formation," ApJS, 123, 3

Liang, C. J., & Chen, H.-W. 2014, "Mining circumgalactic baryons in the low-redshift universe," MNRAS, 445, 2061

Lilly, S. J., Carollo, C. M., Pipino, A., Renzini, A., & Peng, Y. 2013, "Gas Regulation of Galaxies: The Evolution of the Cosmic Specific Star Formation Rate, the Metallicity-Mass-Star-formation Rate Relation, and the Stellar Content of Halos," ApJ, 772, 119

Lopez, L. A., Krumholz, M. R., Bolatto, A. D., Prochaska, J. X., Ramirez-Ruiz, E., & Castro, D. 2014, "The Role of Stellar Feedback in the Dynamics of H II Regions," ApJ, 795, 121

Lopez, L. A., Krumholz, M. R., Bolatto, A. D., Prochaska, J. X., & Ramirez-Ruiz, E. 2011, "What Drives the Expansion of Giant H II Regions?: A Study of Stellar Feedback in 30 Doradus," ApJ, 731, 91

Macciò, A. V., Stinson, G., Brook, C. B., Wadsley, J., Couchman, H. M. P., Shen, S., Gibson, B. K., & Quinn, T. 2012, "Halo Expansion in Cosmological Hydro Simulations: Toward a Baryonic Solution of the Cusp/Core Problem in Massive Spirals," ApJ, 744, LL9

Maller, A. H., & Bullock, J. S. 2004, "Multi-Phase Galaxy Formation: High-velocity Clouds and the Missing Baryon Problem," MNRAS, 355, 694

Mannucci, F., Cresci, G., Maiolino, R., Marconi, A., & Gnerucci, A. 2010, "A Fundamental Relation between Mass, Star Formation Rate and Metallicity in Local and High-Redshift Galaxies," MNRAS, 408, 2115

Martin, C. L., & Bouché, N. 2009, "Physical Conditions in the Low-ionization Component of Starburst Outflows: The Shape of Near-Ultraviolet and Optical Absorption-line Troughs in Keck Spectra of ULIRGs," ApJ, 703, 1394

Martin, C. L., Shapley, A. E., Coil, A. L., Kornei, K. A., Bundy, K., Weiner, B. J., Noeske, K. G., & Schiminovich, D. 2012, "Demographics and Physical Properties of Gas Out/Inflows at $0.4 < z < 1.4$," arXiv:1206.5552

Matejek, M. S., Simcoe, R. A., Cooksey, K. L., & Seyffert, E. N. 2012, Mg II Absorption at $2 < z < 6$ with Magellan/FIRE. II: A Longitudinal Study of H I, Metals, and Ionization in Galactic Haloes," arXiv:1207.2470

Murray, N., & Rahman, M. 2010, "Star Formation in Massive Clusters Via the Wilkinson Microwave Anisotropy Probe and the Spitzer Glimpse Survey," ApJ, 709, 424

National Research Council, Committee for a Decadal Survey of Astronomy and Astrophysics 2010, "New Worlds, New Horizons in Astronomy and Astrophysics," NRC, ISBN 978-0-309-15799-5

Navarro, J. F., & Benz, W. 1991, "Dynamics of cooling gas in galactic dark halos," ApJ, 380, 320

Navarro, J. F., & Steinmetz, M. 2000, "Dark Halo and Disk Galaxy Scaling Laws in Hierarchical Universes," ApJ, 538, 477

Navarro, J. F., & White, S. D. M. 1993, "Simulations of Dissipative Galaxy Formation in Hierarchically Clustering Universes - Part One - Tests of the Code," MNRAS, 265, 271

Nielsen, N. M., Churchill, C. W., & Kacprzak, G. G. 2013b, "MAGIICAT II. General Characteristics of the Mg II Absorbing Circumgalactic Medium," ApJ, 776, 115

Nielsen, N. M., Churchill, C. W., Kacprzak, G. G., & Murphy, M. T. 2013a, "MAGIICAT I. The Mg II Absorber-Galaxy Catalog," ApJ, 776, 114

Nielsen, N. M., Churchill, C. W., Trujillo-Gomez, S., & Kacprzak, G. G. 2014, "The Quantified Behavior of Mg II Kinematics with Galaxy Properties," ApJ, submitted

Pellegrini, E. W., Baldwin, J. A., & Ferland, G. J. 2011, "Structure and Feedback in 30 Doradus. II. Structure and Chemical Abundances," ApJ, 738, 34

Oppenheimer, B. D., & Davé, R. 2008, "Mass, Metal, and Energy Feedback in Cosmological Simulations," MNRAS, 387, 577

Rakic, O., Schaye, J., Steidel, C. C., & Rudie, G. C. 2012, " Neutral Hydrogen Optical Depth near Star-forming Galaxies at $z \sim 2.4$ in the Keck Baryonic Structure Survey," ApJ, 751, 94

Riebe, K., Partl, A. M., Enke, H., Forero-Romero, J., Gottlöber, S., Klypin, A., Lemson, G., Prada, F., Primack, J. R., Steinmetz, M., & Turchaninov, V. 2013, "The MultiDark Database: Release of the Bolshoi and MultiDark cosmological simulations," Astronomische Nachrichten, 334, 691

Rubin, K. H. R., Prochaska, J. X., Koo, D. C., & Phillips, A. C. 2011, "The Direct Detection of Cool, Metal-enriched Gas Accretion onto Galaxies at $z \sim 0.5$," ApJ, 747, 26

Rubin, K. H. R., Weiner, B. J., Koo, D. C., Martin, C. L., Prochaska, J. X., Coil, A. L., Newman, J. A. 2010, "The Persistence of Cool Galactic Winds in High Stellar Mass Galaxies between $z \sim 1.4$ and 1," ApJ, 719, 1503

Rudie, G. C., Steidel, C. C., Trainor, R. F., Rakic, O., Bogosavljević, M., Pettini, M., Reddy, N., Shapley, A. E., Erb, D. K., & Law, D. R. 2012, "The Gaseous Environment of High-z Galaxies: Precision Measurements of Neutral Hydrogen in the Circumgalactic Medium of $z \sim 2$–3 Galaxies in the Keck Baryonic Structure Survey," ApJ, 750, 67

Savage, B. D., & Sembach, K. R. 1991, "The analysis of apparent optical depth profiles for interstellar absorption lines ," ApJ, 379, 245

Scannapieco, C., Tissera, P. B., White, S. D. M., & Springel, V. 2008, "Effects of supernova feedback on the formation of galaxy discs,"MNRAS, 389, 1137

Schaye, J., Crain, R. A., Bower, R. G., Furlomg, M., Schaller, M., Theuns, T., Dalla Vecchia, C., Frenk, C. S., McCarthy, I. G., Helly, J. C., Jenkin, A., Rosas-Guevara, Y. M., White, S. D. M., Baes, M., Booth, C. M., Camps, P., Navarro, J. F., Qu, Y., Rahmati, A., Sawala, T., Thomas, P. A., & Trayford, J. 2014, "The EAGLE project: Simulating the evolution and assembly of galaxies and their environments," arXiv:1407.7040

Schaye, J., Dalla Vecchia, C., Booth, C. M., et al. 2010, "The physics driving the cosmic star formation history," MNRAS, 402, 1536

Simcoe, R. A., Sargent, W. L. W., Rauch, M., & Becker, G. 2006, "Observations of Chemically Enriched QSO Absorbers near $z \sim 2.3$ Galaxies: Galaxy Formation Feedback Signatures in the Intergalactic Medium," ApJ, 637, 648

Sommer-Larsen, J., Götz, M., & Portinari, L. 2003, "Galaxy Formation: Cold Dark Matter, Feedback, and the Hubble Sequence," ApJ, 596, 47

Springel, V., & Hernquist, L. 2003, "The history of star formation in a *Lambda* cold dark matter universe," MNRAS, 339, 312

Steidel, C. C., Erb, D. K., Shapley, A. E., Pettini, Max; Reddy, Naveen; Bogosavljević, M., Rudie, G. C., Rakic, O. 2010, "The Structure and Kinematics of the Circumgalactic Medium from Far-ultraviolet Spectra of $z \simeq 2$–3 Galaxies," ApJ, 717, 289

Stewart, K. R., Kaufmann, T., Bullock, J. S., Barton, E. J., Maller, A. H., Diemand, J., & Wadsley, J. 2011, "Observing Cold Flow Accretion Using Halo Absorption Systems," ApJ, 735, L1

Stewart, K. R., Kaufmann, T., Bullock, J. S., Barton, E. J., Maller, A. H., Diemand, J., & Wadsley, J. 2011, "Orbiting Circumgalactic Gas as a Signature of Cosmological Accretion," ApJ, 738, 39

Stocke, J. T., Keeney, B. A., Danforth, C. W., Shull, J. M., Froning, C. S., Green, J. C., Penton, S. V., & Savage, B. D. 2013, "Characterizing the Circumgalactic Medium of Nearby Galaxies with HST/COS and HST/STIS Absorption-line Spectroscopy," ApJ, 763, 148

Teyssier, R., Chapon, D., & Bournaud, F. 2010, "The Driving Mechanism of Starbursts in Galaxy Mergers," ApJ, 720, L149

Thacker, R. J., & Couchman, H. M. P. 2000, "Implementing Feedback in Simulations of Galaxy Formation: A Survey of Methods," ApJ, 545, 728

Trainor, R. F., & Steidel, C. C. 2012, "The Halo Masses and Galaxy Environments of Hyperluminous QSOs at $z \simeq 2.7$ in the Keck Baryonic Structure Survey," ApJ, 752, 39

Tremonti, C. A., Heckman, T. M., Kauffmann, G., Brinchmann, J., Charlot, S., White, S. D. M., Seibert, M., Peng, E. W., Schlegel, D. J., Uomoto, A., Fukugita, M., & Brinkmann, J. 2004, "The Origin of the Mass-Metallicity Relation: Insights from 53,000 Star-forming Galaxies in the Sloan Digital Sky Survey," ApJ, 613, 898

Tremonti, C. A., Moustakas, J., & Diamond-Stanic, A. M. 2007, "The Discovery of 1000 km s^{-1} Outflows in Massive Poststarburst Galaxies at $z = 0.6$," ApJ, 663, L77

Tripp, T. M., Meiring, J. D., Prochaska, J. X., Willmer, C. N. A., Howk, J. C., Werk, J. K., Jenkins, E. B., Bowen, D. V., Lehner, N., Sembach, K. R., Thom, C., & Tumlinson, J. 2011, "The Hidden Mass and Large Spatial Extent of a Post-Starburst Galaxy Outflow," Science, 334, 952

Trujillo-Gomez, S., Klypin, A., Colin, P., Ceverino, D., Arraki, K., & Primack, J. 2013, "Low-Mass Galaxy Assembly in Simulations: Regulation of Early Star Formation by Radiation from Massive Stars," arXiv:1311.2910

Trujillo-Gomez, S., Klypin, A., Primack, J., & Romanowsky, A. J. 2011, "Galaxies in ΛCDM with Halo Abundance Matching: Luminosity-Velocity Relation, Baryonic Mass-Velocity Relation, Velocity Function, and Clustering," ApJ, 742, 16

Tumlinson, J., Thom, C., Werk, J. K., Prochaska, J. X., Tripp, T. M., Weinberg, D. H., Peeples, M. S., O'Meara, J. M., Oppenheimer, B. D., Meiring, J. D., Katz, N. S., Davé, R., Ford, A. B., & Sembach, K. R. 2011, "The Large, Oxygen-Rich Halos of Star-Forming Galaxies Are a Major Reservoir of Galactic Metals," Science, 334, 948

Tumlinson, J., Thom, C., Werk, J. K., Prochaska, J. X., Tripp, T. M., Katz, N., Davé, R., Oppenheimer, B. D., Meiring, J. D., Ford, A. B., O'Meara, J. M., Peeples, M. S., Sembach, K. R., & Weinberg, D. H. 2013, "The COS-Halos Survey: Rationale, Design, and a Census of Circumgalactic Neutral Hydrogen," ApJ, 777, 59

van de Voort, F., Schaye, J., Booth, C. M., Haas, M. R., & Dalla Vecchia, C. 2011, "The Rates and Modes of Gas Accretion on to Galaxies and their Gaseous Haloes," MNRAS, 414, 2458

Vogelsberger, M., Genel, S., Sijacki, D., Torrey, P., Springer, V., & Hernquist, L. 2013, "A model for cosmological simulations of galaxy formation physics," MNRAS, 436, 3031

Weiner, B. J., Coil, A. L., Prochaska, J. X., Newman, J. A., Cooper, M. C., Bundy, K., Conselice, C. J., Dutton, A. A., Faber, S. M., Koo, D. C., Lotz, J. M., Rieke, G. H., & Rubin, K. H. R. 2009, "Ubiquitous Outflows in DEEP2 Spectra of Star-Forming Galaxies at $z = 1.4$," ApJ, 692, 187

Werk, J. K., Prochaska, J. X., Tumlinson, J., Peeples, M. S., Tripp, T. M., Fox, A. J., Lehner, N., Thom, C., O'Meara, J. M., Ford, A. B., Bordoloi, R., Katz, N., Tejos, N., Oppenheimer, B. D., Davé., R., & Weinberg, D. H. 2014, "The COS-Halos Survey: Physical Conditions and Baryonic Mass in the Low-redshift Circumgalactic Medium," ApJ, 792, 8