D1. Intellectual Merit: The Spatially Resolved CGM

How and when do galaxies form their disks? How do some transform over time into passive spheroids? These two deep questions drive research today even though they are among the oldest in astronomy. Deep surveys have traced the rise of disks back to $z > 3$ (Simons et al., 2017) and the growth of the "red sequence" almost as far back. Around $z \sim 1$, star forming disks and passive spheroids make up roughly equal parts of the massive galaxy population (Brammer et al., 2012). Somehow the disks "quench," turning passive, but we do not know *how* this happens.

A problem this complex demands multifaceted solutions. We posit that many of the answers to how galaxies evolve lie in the circumgalactic medium (CGM), the diffuse gas reservoir where accretion from the intergalactic medium meets ejected feedback, where metals mix and recycle, and where, potentially, the galaxies' gas supply is ultimately regulated (Tumlinson, Peeples, & Werk, 2017). **Our integrated program of numerical simulations and state-of-the-art observations will unify our high-resolution galaxy/CGM simulations (FOGGIE; Figuring Out Gas & Galaxies In Enzo) with a sample of new and re-analyzed archival data on spatially-resolved CGM gas to provide a fresh angle on the role of the CGM in the formation of disks and their transition to passive spheroids.**

The most compelling future measurements of the CGM (for us at least) will come from integral-field spectrographs (IFS or IFUs) on the VLT and Keck (and ELTs) that enable *spatially-resolved* observations of CGM gas. With strong gravitational lensing, quasars are multiply-imaged and galaxies are stretched into prominent arcs, becoming spatially-resolved probes of a foreground galaxy's CGM, which we can now see in two dimensions (Figure 1). The Keck/KCWI and VLT/MUSE instruments are leading a revolution in this field. Already numerous archival IFU measurements of resolved arcs can be applied to studying intervening CGM absorption (e.g., Lopez et al., 2018; Péroux et al., 2018). New analyses of large-area surveys are producing high-yield catalogs of 100s of strong single-galaxy lenses (e.g., Diehl et al., 2017 from DES), which we will mine as the basis of new IFU observations. Meanwhile, dozens of relevant past observations, notably spectroscopy of binary and lensed QSOs, have yet to be mined for CGM/galaxy interactions (e.g., Martin et al., 2010). In combination with this wealth of new data, our recent (NSF-supported) advances in high-resolution simulations makes it compelling and feasible for us to reach for new 2D, small scale structure of galaxy/CGM evolution.

There are strong hints of connections between galaxy disks and the CGM. First, a direct correlation between the surface density of CGM gas and the H I mass of the ISM points to the fueling of disks (Borthakur et al., 2016). Kinematic maps of individual galaxies exhibit a consistent sense of "rotation" for galaxies and close-in CGM gas (e.g., recent results by Bouché et al., 2013; Ho et al., 2017). The substantial CGM budgets of baryons (Werk et al., 2014; Prochaska et al., 2017) and metals (Peeples et al., 2014) out to hundreds of kpc suggest coupling between disks and the CGM as a whole. Recent simulations—which typically resolve the CGM to much coarser resolution than FOGGIE—have found links between the disk and CGM angular momentum, through the hot coronal matter (Oppenheimer, 2018) or cold streams that drive the angular momentum into the inner galaxy (Danovich et al., 2015; Stewart et al., 2017; Garrison-Kimmel et al., 2018). With FOGGIE, we have already found disk shape, size, orientation, and angular momentum are sensitive to the simulated CGM resolution (Figure 5), as are the absorption-line observables with which the CGM itself is measured (Peeples et al., 2018). The burgeoning IFU datasets enable access to new observables near real galaxy disks—such as shear fields and metallicity structure—right at the CGM/disk interface. The combination of such novel data with highly resolved, targeted simulations have great potential for new insights into how CGM/disk interactions operate.

Quenched galaxies pose a major conundrum that hints at deeper insights into CGM/galaxy

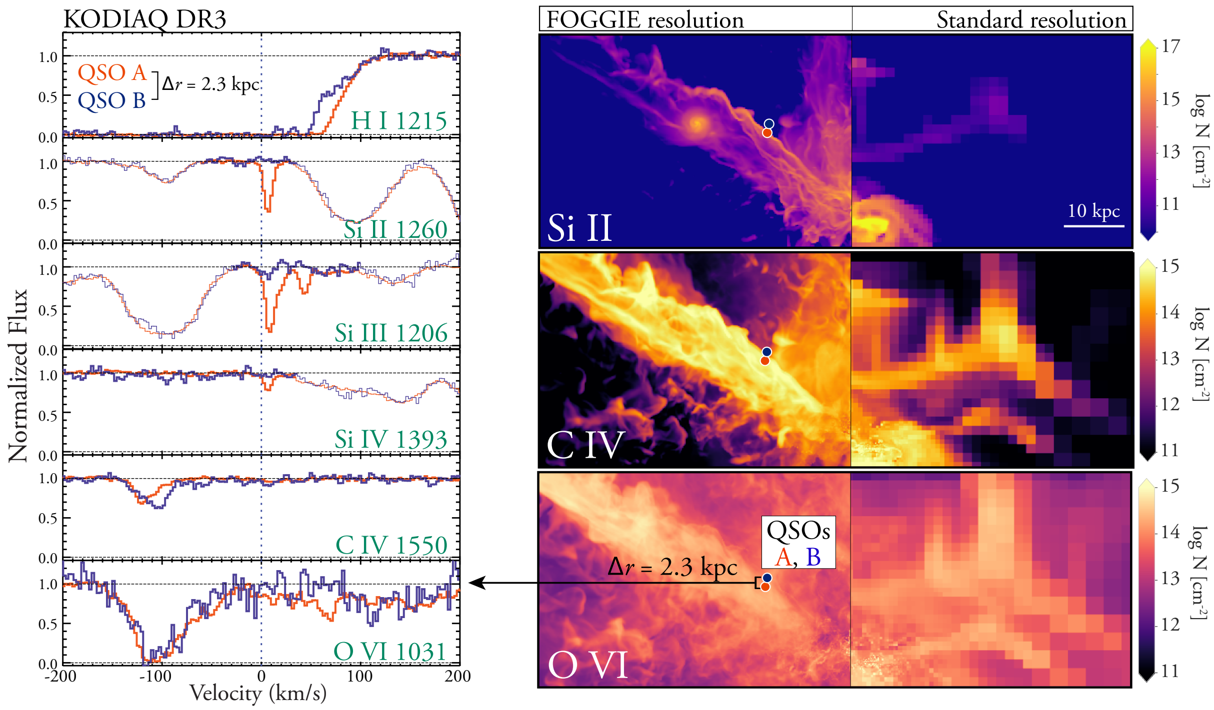

Figure 1: The importance of spatially resolving the CGM. Two Keck/HIRES spectra of absorption with very different profiles along sightlines only 2.3 kpc apart. The simulation renders splice together two runs of the same galaxy at the same time with standard resolution (*far right*) versus FOGGIE's resolution (*left*). The CGM has rich structure at sub-kpc scales: our planned BEARS observations of the spatially-resolved CGM must have simulations with spatial resolution sufficient to draw meaningful comparisons.

interactions. Early predictions for how the CGM would appear in quenched galaxies (Kereš et al., 2005; Stewart et al., 2011) suggested a near total absence of cold gas. Observations disagreed, however, as $\sim L^*$ passive galaxies harbor as much H I as star-forming galaxies of similar stellar masses (Thom et al., 2012; Tumlinson et al., 2013). They are, however, deficient in warm ionized halo gas ($T \sim 10^5$ K; Tumlinson et al., 2011), which may indicate that their halos are hotter than this (Oppenheimer et al., 2016). Targeted studies of Large Red Galaxies (LRGs; $\langle \log M_{\rm halo} \rangle \approx 13.4$) have found large amounts of cold gas (Chen et al., 2018; Berg et al., 2018), while still generally exhibiting deficits of warm-ionized gas absorption (Zahedy et al., 2018; Howk et al., 2018).

To address these puzzles, Voit et al. (2015) described a theory "precipitation" of cold CGM gas from a hot medium in places where the cooling times are short enough to allow efficient cloud condensation. Precipitation from the hot halos of passive galaxies could help explain the presence of cold gas, were it not for the fact that a third of the detections have low metallicities ($Z < 1/300\,Z_\odot$)—too low to have originated in the hot halo (Zahedy et al., 2018; Berg et al., 2018). The precipitation theory also does not explain why the cooled gas does not fall to the galaxy center on a free fall time and trigger star formation, which remains a mystery. Numerical simulations can quench simulated galaxies by heating or removing their CGM gas (Gabor & Davé, 2012; Vogelsberger et al., 2014). But so far none have succeeded in quenching galaxies while leaving more than a trace CGM, and none have explained why the cold gas that is observed does not do what it "should": cool into the ISM. We have two fresh angles on this problem. First, the FOGGIE simulations, with $M \sim 10$–$100\ {\rm M}_\odot$ mass resolution, have a better chance of resolving precipitation in realistic massive galaxy halos than prior simulations with $M \gtrsim 10^{3-4}\ {\rm M}_\odot$ particles. Second, and crucially for our goals, lensed galaxies that become arcs *favor* CGM probes close to quenched galaxies; within a few effective radii and inside the "precipitation radius" (Voit et al., 2015). Studies of such close, 2D probes will soon approach the sample sizes of the traditional pencil-beam studies, making them an extremely promising avenue for addressing quenching over $0 < z < 3$.

To address the formation of disks and the quenching of galaxies from this new perspective, we are following a roadmap that combines groundbreaking simulations with state-of-the-art data. Our group's focus and strength lies in our closely coupled program of data and theory, which continuously guide each other in a mutually reinforcing fashion. Our experience as a unified group so far, and as separate investigators before, shows that this integrated approach promises better intuition, deeper insights, faster progress, and more breakthroughs, than working in a conventional decoupled way. Funded by NSF and NASA, we have achieved an unprecedented numerical (spatial and mass) resolution simulated CGM gas (Figure 1), which turns out to be a critical factor in properly testing theory with data from absorption lines (Peeples et al., 2018) and emission (Corlies et al., 2018). So far, we have focused on properly resolving the gas flows in the CGM, and connecting these rigorously to observed absorption-line diagnostics using mock data. However, we are currently funded only for the part of the roadmap that brings our simulations and datasets to $z = 2$, with a focus on comparing FOGGIE to data from CGM absorption lines and narrow-field JWST imaging and IFUs. To meet our science goal of examining disk formation and quenching with from these fresh angles, we must (1) aggregate existing IFU data and collect more, (2) run our existing simulations down past $z = 1$, (3) make the leap to the forthcoming exascale version of Enzo (Enzo-E), and (4) integrate all these items into a coherent analysis. This proposal asks for support of all these program elements. In addition to its potential for scientific advances, our program will train the next generation of astronomers in both observational *and* theoretical tools, supporting 2 years of postdoctoral training and two PhD theses. Our program will achieve its broader impacts through the training and mentoring of young scientists, including underrepresented groups, and in the creation of pedagogical visualization for teaching and outreach materials for classrooms, museums, and the web. It is our understanding that NSF AAG is the *only* major research grant opportunity suitable for such a joint observational+theory program.

For ease of reading, the "Program Description" describes the essential program elements at a high level within the first eight pages (D2–D5). D6–D12 elaborate on our plans with more technical details, including answers to questions that might arise over the course of the proposal (D13).

D2. Group Profile And Previous NSF Results

Figure 2 shows our group roadmap, which relates major program elements and findings to the source of funding for our past, present, and future efforts. We have been funded by NSF since 2015 (AST-1517908; "Collaborative Research: Multiscale Physics and Feedback in Real and Simulated Circumgalactic Gas Over Cosmic Time"; PI Peeples, Co-PIs Tumlinson, Howk, Lehner, O'Shea, O'Meara; $833,170, 09/2015–08/2019, with the main tranche of funding beginning 09/2016). **Intellectual Merits:** This NSF funding (coded red in the timeline) supported both the initial stages of FOGGIE and the second data release of the KODIAQ project. With FOGGIE, we pioneered a novel "forced refinement" scheme in Enzo, which resolves the CGM at mass resolutions of 10–100 Msun (or 10–1000 times finer than the previous state of the art). We simulated a single, Milky Way-like halo to $z = 2$ to develop the forced-refinement scheme. The simulations were run at NCSA's Blue Waters, TACC's Stampede 2, and NASA's Pleiades (the latter through a time-sharing arrangement with a NASA-funded project that uses the same code and initial conditions). Over the course of our funded NSF program, our group has secured 6.2 million CPU hours at Stampede2 (PI Corlies) and Blue Waters (PI Peeples). By generating and interpreting mock absorption line spectra, linked rigorously back to the gas, we found the increased resolution fundamentally changes the sizes, masses, and kinematics of the clouds making up the mock absorption. These results strongly suggest that

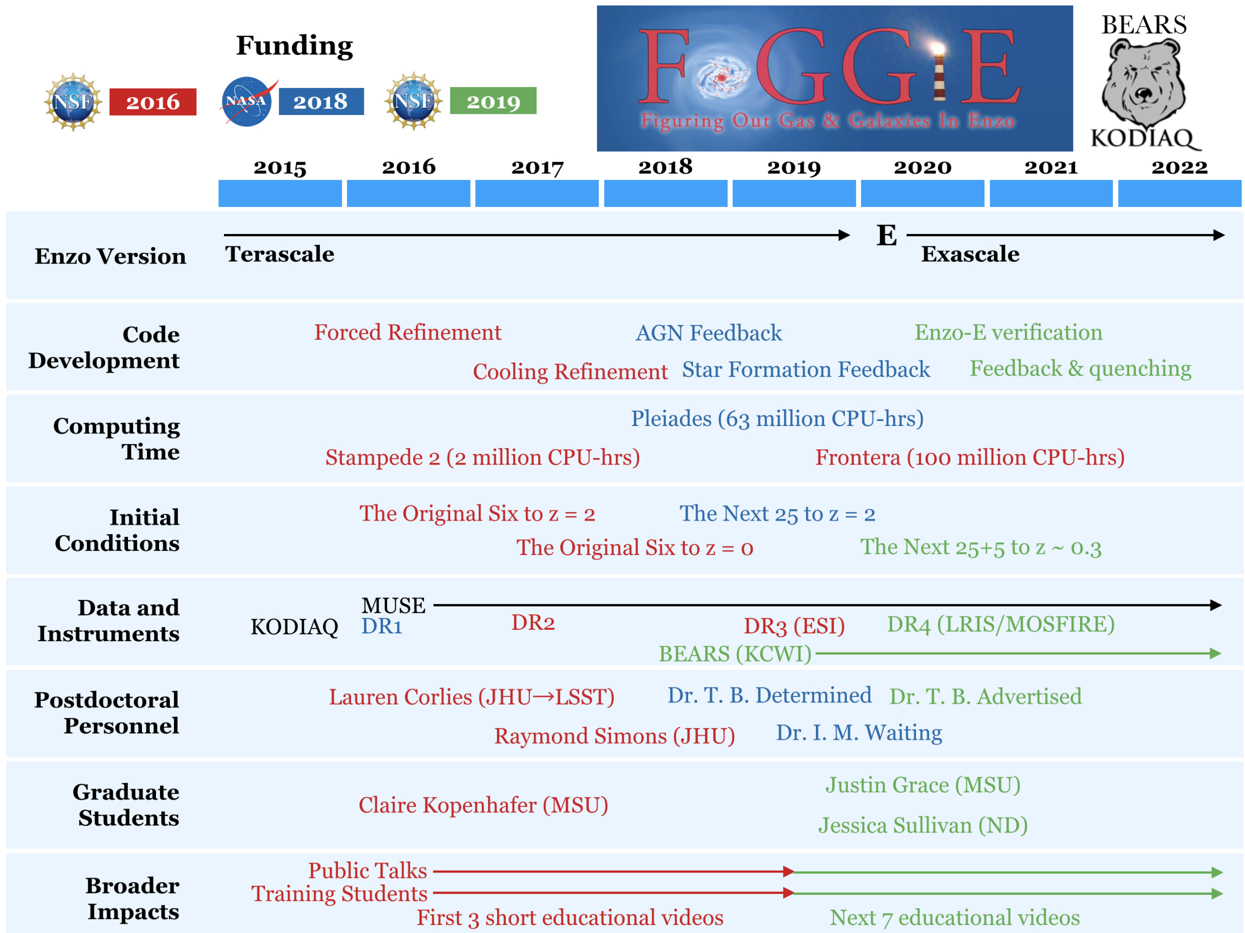

Figure 2: A funding-coded roadmap for our collaboration. We were originally funded by the NSF (red) and continue FOGGIE under the NASA Astrophysics Theory Program (ATP; blue). The green items are proposed here as a second round of NSF support. Alignments with calendar years are approximate. Note that the focus of Part III on ground-based data is unsuitable for present or continuing NASA support.

drawing the long-desired direct links between galaxy gas flows and CGM observables requires fine mass resolution and close attention to the detailed kinematic structure giving rise to the absorption and emission (Peeples et al., 2018; Corlies et al., 2018). We have three more FOGGIE papers based on the full set of six halos in the pipeline for 2019 (the last year of NSF funding). We returned the second KODIAQ (Keck Observatory Database of Ionized Absorption Toward Quasars) data release containing fully-reduced spectra of 300 quasars from the Keck HIRES archive, which serves as the $z > 2$ comparison set for FOGGIE (O'Meara et al., 2017). This effort made decades of high-quality HIRES spectra publicly accessible for the first time, a huge legacy value far beyond our own science goals. We developed a method for deriving metallicities for dense CGM requiring $\sim 10\times$ less observing time, based on the adoption of Bayesian priors on ionization conditions (Wotta et al., 2016, 2018).

Broader Impacts: Our current grant has enjoyed a variety of broader impacts. First, we have supported a total of five undergraduates in their research projects (four at MSU and one at JHU). Four of these are from underrepresented groups in STEM; three have already started PhD programs (the other two probably will also when they finish their undergrad degrees). We used our simulation data to train students at MSU in scientific visualization and data analysis techniques. We have also worked with several professional science writers to bring the story of the CGM to a wider audience.[1] Finally, we are developing a series of short YouTube videos for educational purposes describing circumgalactic gas and how it is observed using a combination of visuals from the simulations and Keck data; these videos will also be hosted on the FOGGIE webpage[2].

We recently began the second phase of our roadmap, funded by NASA's Astrophysics Theory Program (ATP) and coded blue in Figure 2. A new set of simulations will expand the FOGGIE universe to 25 halos over 0.1–10 L* and produce mock data tuned for surveys of the $z > 2$ galaxy populations by the *James Webb Space Telescope*. These simulations will directly address the kinematics of disks and spheroids that fit into the 3–5″ field of view of JWST's Integral Field Units (IFUs), which will excel at producing kinematically-resolved maps of high-z galaxies. This NASA-funded second generation will *not* run below $z < 2$—and will not address the joint CGM-galaxy observations that are possible with the new generation of ground-based IFUs (e.g. MUSE and KCWI). These new possibilities motivate our current proposal.

D3. BEARS: New Forms Of Circumgalactic Data

The observational component of our program, Baryon Exploration via Absorption Resolved Spatially (BEARS), will combine multiple data sources from publicly available archives, proprietary data in hand, and new observations. Most of our observational constraints on the CGM arise from absorption-line measurements along single sight lines through individual galaxy halos. Understanding the distribution and halo-scale dynamics of the CGM requires compiling ensembles of galaxies and/or absorbers, hopefully in a homogeneous way. At $z < 1$, *Hubble Space Telescope* observations of the CGM have been coupled with galaxy properties for < 100 objects—quantities like star formation rate, morphology and inclination—to constrain the role the CGM plays in shaping these properties, though usually still on a one galaxy-one sight line basis (e.g., COS-Halos). At $z \gtrsim 2$, there are now > 500 sightlines for probing the CGM of intervening galaxies with high spectral resolution and moderate to high signal to noise thanks to 8–10 meter class telescopes (O'Meara et al., 2017; Murphy et al., 2018). This class of data—single sight line, high spectral resolution absorption spectroscopy—has provided the main repository for information on the CGM for decades.

The single sight line approach has proven powerful as a first glance at the physics of the CGM: it is sensitive to extremely low gas densities and effective over nearly all redshifts. Still, all these data provide essentially 1D views of gas flows with rich underlying 6D spatial and kinematic structures that dictate the overall evolution of the CGM and its importance for star formation. The availability of new IFU spectrographs is allowing us now to push the frontier toward spatially-sampled CGM data and thus overcome some of the key limitations of pencil-beam absorption. This new data frontier includes IFU observations of single galaxies that can resolve their disks and the nearby CGM, of multiple QSOs—lensed and projected—probing the CGM (of both the lensing and intervening galaxies), and of extended background sources created by strong lenses that provide a tomographic view of the CGM (Figure 3; D11). These spatially-sampled measurements of the CGM of galaxies are complementary to the tried-and-true 1D methods. There are already several proofs of the basic concept (e.g., Lopez et al., 2018; Péroux et al., 2018; Rahmani et al., 2018), and although we do not yet know how much information they will yield about the CGM mass, metallicity, kinematics, and physics of the CGM gas, these case studies demonstrate a new way to explore the distribution and sizes of the metals and baryons in the CGM. The sample sizes are rapidly increasing, driven in particular by new methods for discovering hundreds of lensed sources. We can already project from current literature and expected surveys that dozens to hundreds of spatially-sampled CGM observations will exist in the public domain within the next few years. *Now* is the time to learn

[1] See, e.g., Grossman (2018).
[2] http://foggie.science/

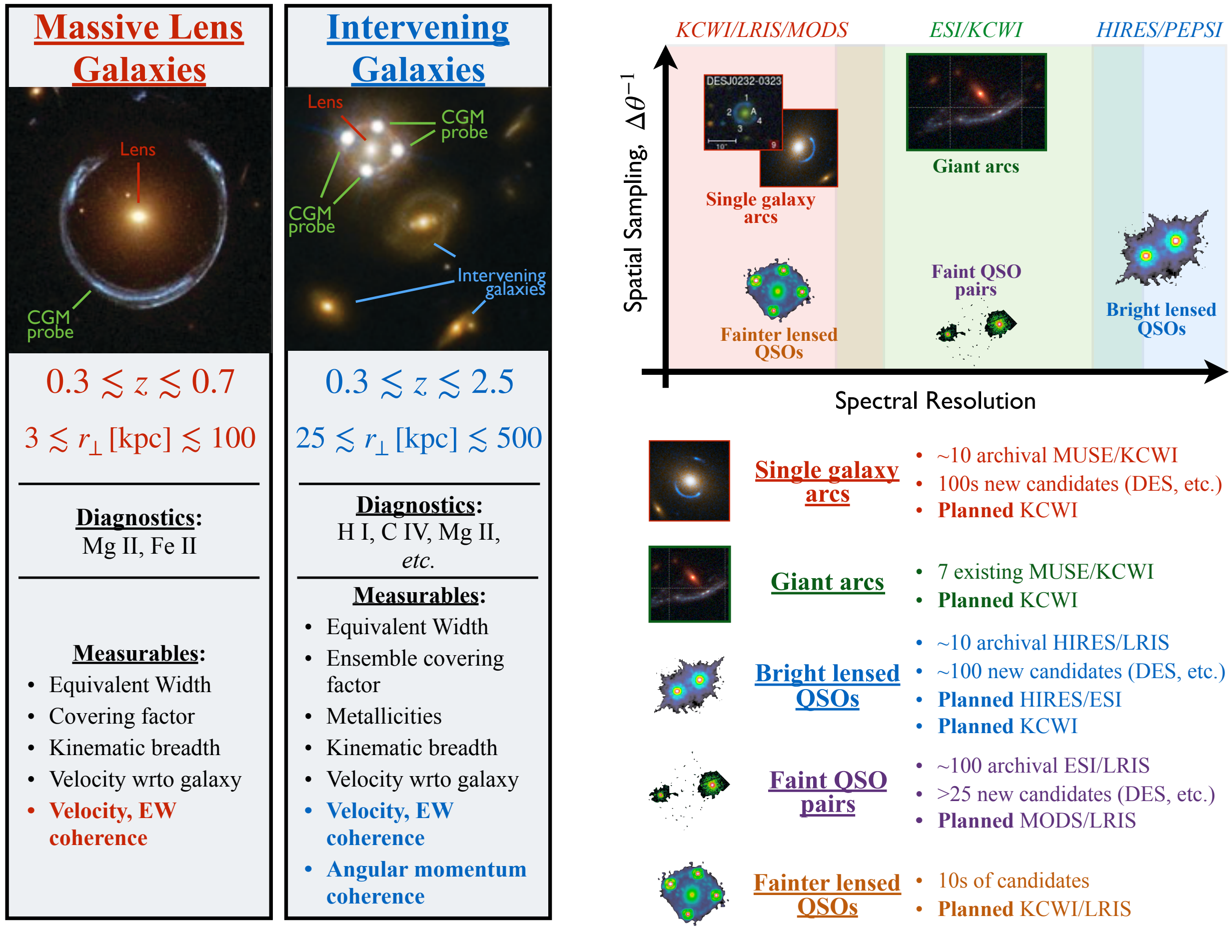

Figure 3: An overview of the observational component of our program. The two categories of target galaxies are shown on the *left*, the massive lensing galaxies and unrelated intervening galaxies; we summarize the redshift and impact parameter ($r_\perp$) ranges of our samples along with the diagnostics and measurables we will target in each case. Because of their low-redshift, the massive lenses have fewer diagnostics available. The *right* shows a breakdown of the types of sources we will use to probe these galaxies. The *top right* shows a schematic of the relative scale of the spatial sampling each type of source provides and the relative spectral resolutions typically available. The *bottom right* details the number of archival datasets that exist and the types of new observations we plan to pursue with our guaranteed LBT and Keck time.

how to decipher the CGM properties hidden in these data.

The focus of the BEARS data will be using spatially resolved data to spatially map the kinematics of H I and metal ions and couple these diagnostics back to the properties of the galaxies. Specifically, we will (1) measure the scale of *spatially-resolved* metal ion and even metallicity variation in the CGM; (2) assess the coherency of angular momentum within the CGM and between the CGM and central galaxies; and (3) determine if quenching is a global or local phenomenon within the precipitation region of the most massive galaxies. These goals are consistent with current observational capabilities and address some of the most pressing issues in understanding the role the CGM plays in driving star formation (or its absence) in galaxies.

Connecting the CGM data back to the underlying physics—always our ultimate objective—are the synthetic data that are key to our integrated program. The main challenge with CGM data is that projected quantities like column density are not as sensitive to the underlying physical conditions as we would like. This was the lesson of the first-generation FOGGIE mock absorption data: lower-resolution simulations can obtain realistic-looking column-density maps with under-resolved clouds and incorrect kinematics (Peeples et al., 2018; Corlies et al., 2018; see alsoSuresh et al., 2018; van de Voort et al., 2019), undermining the goal of testing theoretical models with real data. This finding would not have been possible without rigorous mapping between mock data and the underlying simulation outputs, which allows us to assess whether the data can actually reveal what we truly want to know. This concern is particularly relevant for resolved CGM data, where we will have to learn to cope with effects such as non-uniform background light sources, variable signal-to-noise, and partial covering of extended sources that are generally not major issues for point-like sightline studies. While it is important that we address these effects to draw rigorous links between data and physics (D12), they do not threaten the basic feasibility of the resolved measurements, which are demonstrated in the refereed literature (D6; Figure 4). Given the source redshifts and the incidence frequency of CGM absorbers with redshift (i.e., many per line of sight), BEARS will provide hundreds of spatially-resolved absorption systems.

D4. The Next Generation Of FOGGIE Simulations

High resolution simulations of galaxies and their CGM are the essence of the FOGGIE project. To address the problems of disk formation and quenching, which are best addressed at $z = 0.3 - 3$, we will evolve 30 galaxies spanning 0.1–10 L^* to $z \sim 0$. We have developed two new refinement schemes to make this computationally feasible while still physically interesting: (1) "cooling refinement", wherein we force the gas to be have its cooling length resolved (the cooling length is defined as the product of the cooling time and speed of sound) and (2) "nested refinement" wherein we can allow the inner CGM to be refined to smaller scales (via either uniform refinement or cooling refinement) than the outer CGM. Because of their larger sizes and higher masses, both of these methods will be necessary for the quenched galaxies to reach $z \lesssim 0.5$. In general we will aim for $\lesssim 40$ physical pc resolution in the ISM and cooling-refined inner CGM, ~ 80 physical pc in the uniformly-refined inner CGM, and $\lesssim 200$ physical pc out to the virial radius, with the exact differentiation between "inner" and "outer" depending on the halo mass (D8).

Even with these modifications to our refinement scheme, the number of computational cells for a $10L^*$ halo would exceed what Enzo can currently handle by about two orders of magnitude. This is purely a computational limitation, the result of a code that was designed in the 1990s, which does not scale well beyond 10,000 threads. Our goal of simulating quenching and the CGM in massive halos forces us to make the transition to the new, re-designed "Enzo-E" (Exascale) during the course of this project. Enzo-E will be usable for the types of simulations described in this proposal in approximately one year's time (i.e., within a few months of this grant's start date). Given Enzo-E's vastly improved scalability over Enzo, even though our simulations will not push far past the current resolution limits we will be able to refine larger regions surrounding galaxies, and thus track CGM physics in more massive galaxies, at modestly higher resolution than we do today (D7; Figure 6). Thus, Enzo-E is critical to applying FOGGIE-style extreme resolution and analysis to massive galaxies, and we plan for the FOGGIE project to transition fully to the Enzo-E (Exascale) code during the course of this project. NSF support will enable this leap.

Once we have the tools—Enzo-E and the necessary physics ported into it—we will still have to produce galaxies that quench (FOGGIE already produces realistically looking disks). This will require some iteration, but we will approach the problem by systematically exploring the range of feedback parameters. If the goal were just merely shut off galactic star formation, this would be relatively easy: heat up and/or expel the gas in the ISM and inner CGM, which has worked in other simulations (Gabor & Davé, 2012; Vogelsberger et al., 2014). We are, however, interested in testing how quenching affects and is affected by changes in the CGM, and in comparing this with spatially-resolved observations of galaxies at the appropriate redshift.

With the feedback methods in place, we will then perform parameter studies to explore the feedback methods and arrive at galaxies that quench. We approach this problem from a different angle compared with most other groups. Instead of tuning (somewhat arbitrary) free parameters for the "subgrid physics," we will instead map out the degree of quenching as a function of the energy, momentum, entropy, and metallicity flux leaving and entering the galaxy. Of course we are changing these physical fluxes by turning knobs on feedback schemes, but the dependent variable in the optimization problem for quenching is not the parameter itself but the physical fluxes into and out of the CGM. This makes the optimization of parameters more physical and more readily compared across galaxy masses (and different codes). By combining this "flux tracking" method with the synthetic data of both the galaxies and the spatially-resolved CGM, we will be closer toward a holistic picture of how feedback and the physics of the CGM affect galaxies and their gaseous halos—and which processes may be more important in the real universe. As Enzo (and Enzo-E) allows users to easily pause and re-start runs with new physics modules, we will probe a large parameter space of feedback fluxes over short timescales without having to re-evolve the same halo multiple times over all of cosmic time.

D5. Broader Impacts: Simulations And Data For Education

The bulk of our broader impacts will be to continue to produce outreach videos, making them available on our website and YouTube and in our mentorship of junior team members. The videos will explore the basics of spectroscopy, gravitational lensing, gas flows through the CGM, and explore topics related to current astronomical techniques—supercomputing and on-site observing—are aimed toward the general public. These will be during public talks given by each of the senior members, and will be linked together as a series to develop a more complete picture of the process of astronomy research (D13). We will continue to train new postdocs and students. Summer undergraduate students at JHU/STScI, MSU, and Notre Dame will join our research program, where they will acquire skills in simulations, analysis code, and presentations. Our students and postdocs receive intensive education in both data *and* theory in addition to mentoring in the more intangible aspects of science that help with career development, grad school applications, job searches, and so on. We will also continue to incorporate our simulation data in computational science courses at MSU and make public the resulting curricular materials.

Technical Details

D6. The Power Of Gravitational Lensing

The power of gravitational lensing for probing the small-scale structure of the CGM is two-fold: first, lensing preserves surface brightness while simultaneously increasing the angular extent of lensed sources on the sky. The net result is that the lensed sources have more overall flux against which foreground circumgalactic structures can be absorbed relative to unlensed sources. The second effect is that lensed objects with a large angular extent on the sky, probing small spatial scales over extended regions at intervening redshifts (Figure 4). Specifically, the physical scale probed by a lensed point source source with a separation $\Delta\theta$ on the sky is given by $\Delta r_{\perp} = \Delta\theta \times D_{\ell} D_{\rm sc}/D_{{\rm s}\ell}$, where D_{ℓ} is the angular diameter distance from the observer to the lens, $D_{\rm sc}$ is the angular diameter distance from the absorbing cloud to the source, and $D_{{\rm s}\ell}$ is the angular diameter distance from the lens to the source (Cooke et al., 2010).[3] For a lensed point source (e.g., a quasar), the physical separation at $z = z_{\rm s}$ is necessarily zero, the physical scale probed by a cloud close to the source redshift can be vanishingly small despite having a large angular size on the sky. Resolved sources are more complicated but the same principle holds. Because the lensing is maximized when the

[3] Recall that in ΛCDM, $D_{z1} + D_{z12} \neq D_{z2}$.

lens is halfway between the observer and the source, most of our lenses will be at $z \sim 0.5$.

D7. Enzo-E: An Exascale Block-Structured Adaptive Mesh Refinement Code

Making the leap to Enzo-E is critical to applying FOGGIE-style extreme resolution to massive galaxies to late cosmic times. Its dramatic improvement over Enzo will enable us to refine larger regions surrounding galaxies—and thus track CGM physics in more massive galaxies—at modestly higher resolution than we can today. Enzo-E (Bordner & Norman, 2018, `http://cello-project.org`) is a next-generation astrophysical simulation code designed from the ground up to maximize performance and scalability on the next generation of supercomputers. It features a "forest of octtrees" data structure coupled to octtree-based adaptive mesh refinement (AMR), and uses the Charm++ parallel framework (Kale et al., 2008, `http://charmplusplus.org/`) to implement asynchronous task execution in an adaptive runtime system. An object-oriented model facilitates separation of the code's physics solvers, infrastructure such as AMR, and underlying parallelism. This model, plus a robust framework for regression and performance testing, enables rapid implementation of new physics modules. After several years of development Enzo-E now delivers near-perfect scalability up to the largest available machines (for scaling plots see Figs. 5 and 6 of Bordner & Norman, 2018). **By design, Enzo-E is vastly more scalable than the original Enzo code** and thus achieves much better run-time efficiency. In Sept. 2018, the Enzo-E development groups received a large, multi-institutional NSF CSSI grant (#OAC-1835426), co-led by Co-PI O'Shea, ensuring that all of the physics solvers that currently exist in Enzo are ported to Enzo-E within the next two years. These items are already funded by the CSSI Enzo-E grant; thus, the only new code development funded by this project in support of our transition to Enzo-E, to be done by the MSU graduate student, is porting the *new* enhancements funded by our ATP program (star formation and feedback, AGN triggering and feedback, and chemical evolution).

D8. Extending The Next Generation Of FOGGIE To $z \sim 0$

The simulation component of this project will consist of 25 halos (first set up and run to $z = 2$ for our NASA project) with an additional five additional massive halos, bringing the overall totals to 5 sub-L^*, 15 L^*, and 10 $> L^*$ galaxies, all simulated at typical FOGGIE resolution. The original profile of 25 halos was chosen to sample a range of halo masses and assembly histories and will

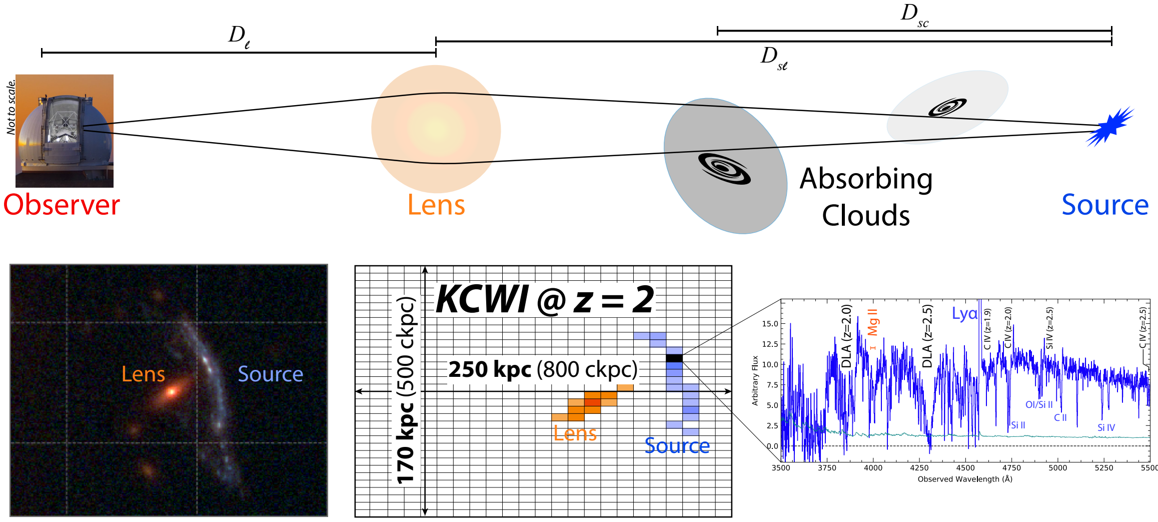

Figure 4: How BEARS leverages gravitational lensing. The upper diagram shows the geometry of the gravitational lens, showing the paths photons take from the source to the observer. The labels across the top correspond to quantities in D6. The bottom diagrams show a *Hubble* image of an arc (in this case lensed by both a cluster and a close galaxy), a schematic of the KCWI format on this source, and a spectrum from a bright knot in our proprietary KCWI data. The size scales for KCWI apply to the field covered for detecting the absorbing galaxies, while the geometry of the source in the absorber plane is more complex.

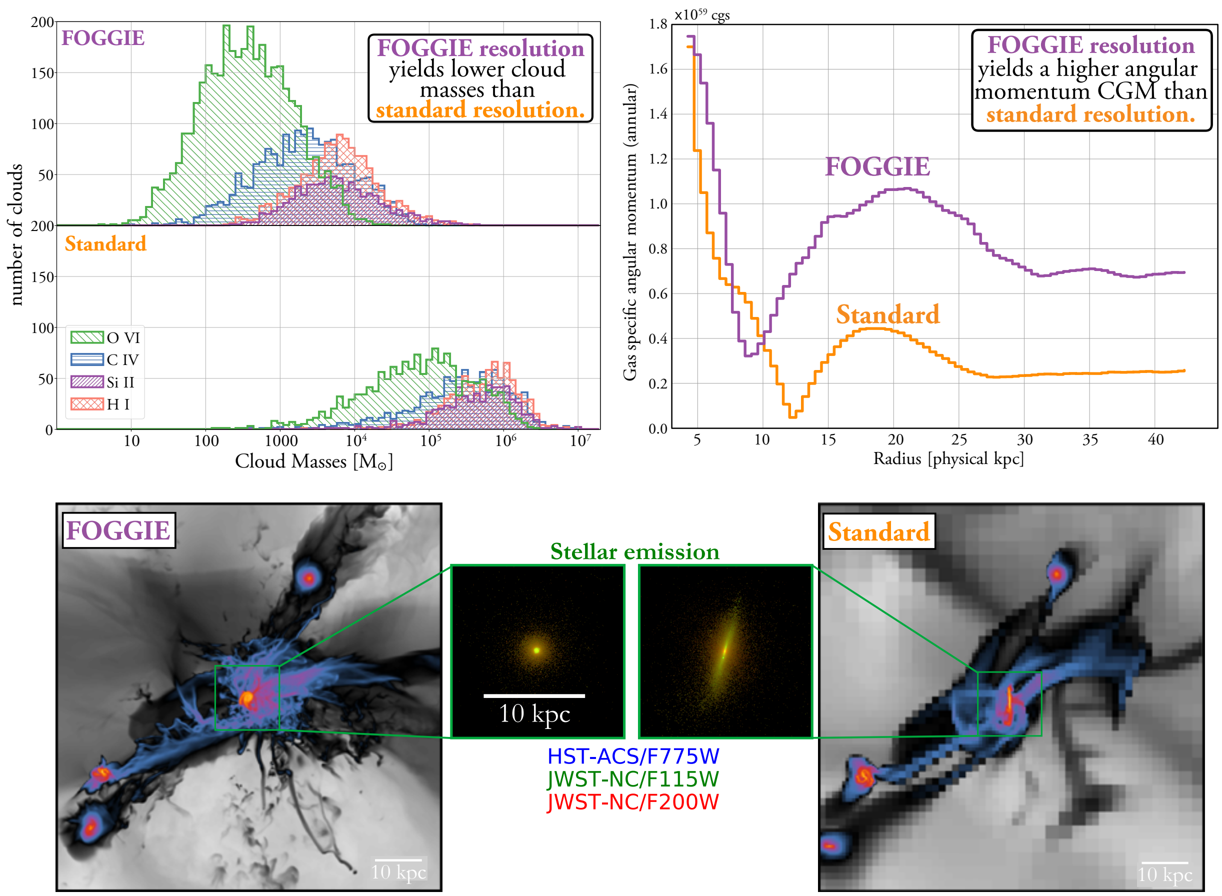

Figure 5: How FOGGIE's high CGM resolution shapes galaxies. At "standard" resolution (lower right, coded orange), the disk is well-resolved but the CGM is not. When high resolution is added to the CGM, the H I columns (*bottom*), disk profile and orientation (*bottom middle*), and the specific angular momentum of the CGM (*top right*) all respond. With finer mass resolution elements in the CGM, the galaxy more easily transfers angular momentum to the CGM, yielding a smaller galaxy and more angular momentum in the CGM. Standard resolution simulations also dramatically under-resolve absorbing clouds (*top left*).

therefore provide us with an interestingly diverse set of galaxy halos. The sub-L^* halos will be chosen to be relatively isolated, as we will naturally pick up sub-L^* satellites in the progenitors to and satellites of the more massive galaxies. Because of their larger sizes and higher stellar masses, the quenched galaxies will present the greatest challenge to complete. To achieve these runs at the desired resolution, we will need to use cooling and nested refinement (described in D4), but also a more efficient code that makes better use of available resources (as no faster computers are on the horizon after Frontera becomes operational). Thus we will transition the FOGGIE project to Enzo-E during the course of this project, led by O'Shea and MSU graduate student Grace, with the JHU postdoc contributing and testing as needed. We estimate that an individual L^* galaxy at typical FOGGIE resolution of 200 pc in the CGM will cost on the order of a million core-hours ($\simeq$ 25,000 node-hours) on Frontera to evolve to $z = 0$, with the computational cost of each galaxy scaling with the virial mass as $\propto M^{4/3}$. We will evolve the smaller ($\leq L^*$) halos to $z = 0$; the more massive halos will require a more nuanced application of our refinement schemes. Because the CGM observations of the LRGs will be at very small impact parameters (Figure 3), we will focus the high-resolution regions of the massive galaxies to the very inner halo, with a somewhat

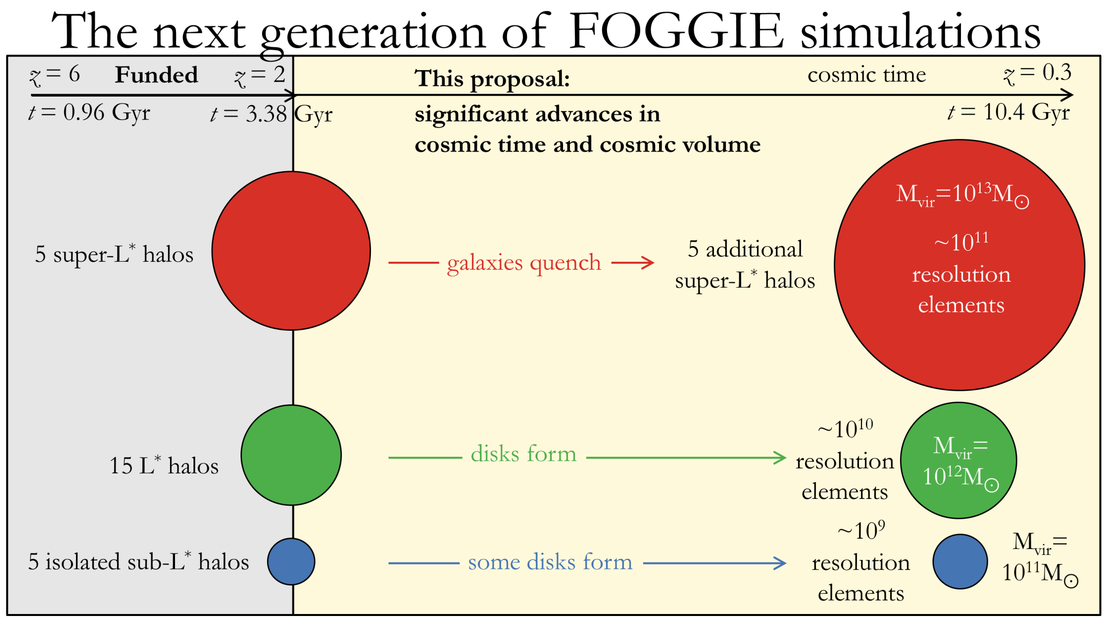

Figure 6: The next generation of FOGGIE halos. The horizontal space is proportional to cosmic time; the circle sizes are proportional to the virial radius at $z = 2$ (*left*) and $z = 0.3$ for halos with $z = 0.3$ virial masses as listed (D8). Our funded ATP program will evolve 25 halos to $z = 2$, but the computational resources to evolve these volumes at FOGGIE resolutions to $z \lesssim 0.5$ will require Enzo-E (D7).

coarser "middle CGM", and yet coarser refinement to the virial radius. In this way, we will scale the number of resolution elements such that we will reach $z \sim 0.5 \pm 0.2$ for the massive halos. For all runs, we will use our new "cooling refinement" based on the cooling length of the gas (in addition to gas density) on top of a uniformly resolved background that reduces unnatural mixing.

Our $z > 2$ work will focus on getting the feedback from massive stars (including pre-supernova effects) and from AGN "correct," but we do not expect for any of these halos to have quenched by this time. The AGN feedback model will be based on prior results by Co-PI O'Shea and collaborators, and will use a jet-based model triggered by cold gas in the vicinity of the supermassive black hole. This AGN feedback framework has been shown by multiple groups to produce reasonable results in galaxy clusters (Gaspari et al., 2013; Li et al., 2015; Meece et al., 2017), and is now being extended to giant ellipticals (Wang et al., 2018). The technical extension to even smaller cosmological halos (i.e, individual L^* galaxies) is straightforward, but ensuring that it produces reasonable results may require some calibration. This implementation will result in a viable framework within which we can vary the relevant stellar and AGN feedback parameters, as described in D4.

D9. Building Galactic Disks: Angular Momentum And Gas Exchange

The CGM plays a crucial role in regulating the angular momentum of galaxies. Most simulations drastically under-resolve circumgalactic gas. As we show in Figure 5, simply increasing the resolution of the simulated CGM can change its angular momentum *by a factor of three*; these changes are reflected in the angular momenta and morphologies of the central galaxies (see, e.g., van der Wel et al., 2014; Ceverino et al., 2015; Swinbank et al., 2017). Combined, FOGGIE and BEARS will provide unique insights into the co-evolution of disks and the CGM.

With absorption along multiple sight lines through individual halos in BEARS data, we will measure the extent to which the angular momentum of the cold gas is coherent (including across the rotational center of the lens galaxy for lensed quasar pairs/quads) and consistent across multiple ionization states (e.g., Mg II, C IV). While the coherency of the angular momentum of the CGM absorption itself is of interest, its correspondence to the central galaxy is critical to understanding how disks form. The IFU data (KCWI, MUSE) we will analyze can provide measures of the orientation and magnitude of angular momentum of ionized gas (and for bright systems, stars) of the intervening galaxies (Genzel et al., 2017; Guo et al., 2018). We will supplement select cases with multi-slit LBT/LUCI data to measure the kinematics of intervening galaxies, taking advantage of the few kpc resolution ($\sim 0.25''$) provided by the ARGOS ground-layer AO system.

In parallel, we will use the FOGGIE high-resolution CGM simulations to assess the exchange of mass and angular momentum between disk and CGM, including the effects of input physics and spatial resolution. At the same time, the FOGGIE simulations will be crucial for understanding the observations. Gas absorption observed at the same line-of-sight velocity is not necessarily cospatial, and can in fact arise from "clouds" tens to hundreds of kiloparsecs apart; likewise, spatially small gas clouds can be sheared or expanding along the line of sight to have a spectral imprint spanning many tens of $\mathrm{km\,s^{-1}}$ (Peeples et al., 2018). While BEARS spatially-sampled measurements help break these degeneracies, we will use synthetic data generated from the FOGGIE simulations to interpret the observations (e.g., what do observed kinematic shears mean given the cloud locations and dynamics? how do those relate back to the angular momentum of the cold CGM?) A primary goal of the mock data will therefore be to develop new metrics for interpreting the spatial variation of kinematic structure of absorption features, specifically in a way that is sensitive to the underlying angular momentum of the CGM. This work will be driven by the JHU postdoc and ND grad student.

D10. Quenching Galaxies... While Maintaining A Cold CGM?!

The arcs and lensed quasars caused by single galaxy lenses sample the massive lensing halos at small impact parameters. They are projected within the precipitation radii for these galaxies, where the ratio of cooling to free fall times $t_{\rm cool}/t_{\rm ff} \lesssim 10$ (impact parameters $5 \lesssim r_\perp \lesssim 50$ kpc; see Figure 3 and Sharma et al. 2012); thus we *expect* condensation of cold gas within these radii. This is born out by the covering factors of strong H I absorption in LRGs, with $f_c \approx 0.3$ for *metal-rich* cold gas within $\sim 0.5 R_{\rm vir}$ (low-metallicity gas adds more; Chen et al., 2018; Berg et al., 2018), $f_c \gtrsim 0.2$ for Mg II, which traces the densest metal-rich clouds (Bowen & Chelouche, 2011; Huang et al., 2016). This cold gas is sufficient to fuel substantial star formation, but it is kept from doing so through unknown quenching mechanisms. How efficient is this quenching? Does it shut off the precipitation process completely, leading to a *global* diminution of cold gas within a majority of LRGs, or does it act on cold clouds once they have formed, producing a *local* destruction within all galaxies?

We will use BEARS' spatially-sampled data to probe the precipitation and quenching mechanisms in the massive galaxy lenses, assessing if this quenching acts globally to shut off precipitation or locally to disrupt cold clouds. Given the Mg II covering fractions about LRGs, if the presence of cold gas due to precipitation is a stochastic occurrence within individual halos, we will rarely see multiple sight lines through a single halo with detectable absorption. However, if precipitation is cut off globally, we expect absorption along multiple sight lines with regularity. The existing analyses of this effect are not sufficient to address the issue (e.g., in a sample of 3 lenses, Zahedy et al. 2016 find a quasar pair in which both show absorption, a pair in which one sight line shows absorption, and a quad in which none shows absorption). BEARS will provide measurements of the cold gas spatial and kinematic correlations across multiple sight lines through ~ 50 massive halos, constraining how these galaxies quench—and stay quenched. The dynamics of the gas will also be an important indicator of the origins of the cold CGM in these galaxies. Precipitation-regulated accretion leads to smaller velocities relative to the galaxy, and relatively little shear, consistent with studies at larger impact parameters (Thom et al., 2012). BEARS data will uniquely constrain this theory by providing measurements of the kinematic structure at *low* impact parameters.

To complement our data we will test the distinction between temporal stochasticity and spatial inhomogeneity with our FOGGIE simulations of massive halos. Most simulations have not resolved the cooling length of CGM gas and so *cannot* study the cool gas observed in massive galaxies if it naturally precipitates from the CGM. By refining specifically on the gas cooling length in the inner halos of massive galaxies, the FOGGIE halos will be uniquely situated to interpret the measurements of the cold gas content in the inner-CGM of LRGs. By approaching our feedback models as parameters in the amount of energy and momentum deposited into certain volumes over certain timescales, we will directly link these physical quantities to the structure and variability of the inner CGM and stellar components of passive galaxies, testing those parameters by comparison with observations (e.g., Wisnioski et al., 2015; Stott et al., 2016; Swinbank et al., 2017). One of the PhD thesis papers by MSU graduate student Grace will focus on how changing the possible quenching mechanisms affects the co-evolution of star formation rates, stellar morphologies, and CGM ionic tracers. At the same time, the simulation work *bears* on our Cycle 25 *Hubble* program[4] that will measure the metallicity distribution of the cold CGM of 50 LRGs; the cold gas has low-metallicities ($\sim 0.01 Z_{\odot}$) $\sim$20% of the time, the origins of which may be traceable with FOGGIE.

D11. BEARS Spatially-Sampled Data Plan

Our BEARS observational program is made up of archival and new data, as summarized in Figure 3. The program will be led by ND graduate student Sullivan with significant support from Howk, Lehner, and O'Meara. The three main classes of circumgalactic probes at different scales are:

A. Large separation quasar pairs ($> 5''$ on the sky): Many quasar pairs ($\Delta\theta \sim$ a few arcsec) have been observed over the last three decades with HIRES/UVES/MIKE ($R \approx 40,000$), ESI/X-shooter (10,000), or LRIS (2,000). These include pairs in the "Quasars Probing Quasars" program (Hennawi et al., 2006; Lau et al., 2018; Findlay et al., 2018) [120 observed with ESI, >350 with LRIS, $\sim$1/2 with $\Delta \leq 500$ kpc at the lower redshift quasar], 130 high-quality quasar pairs from Kirkman & Tytler (2008) [> 30 with $r_{\perp} \leq 500$ kpc for $z\sim1$], and many pairs from smaller programs in the Keck archive. Including additional quasars observed by SDSS/BOSS expands the sample to > 3000 (Findlay et al., 2018). Most were used to study IGM structure (Kirkman & Tytler, 2008) or quasar hosts (Hennawi et al., 2006; Lau et al., 2018); the vast majority have not been mined for measurements of metals in the CGM of foreground galaxies (though see Rubin et al., 2015).

B. Small separation lensed quasar pairs and quads ($< 5''$ on the sky): Lensed quasars provide multiple pencil-beam sightlines through single foreground halos. They have been used to study the scale of metal-line absorption generally in the IGM/CGM (e.g., Rauch et al., 2002) and in a few specific galaxies (Chen et al., 2014; Zahedy et al., 2016) from sub-kpc to 10s of kpc scales. Our BEARS compilation starts with $\sim$10 archival pairs. However, many dozens of good candidates have been identified using machine learning (e.g., Diehl et al., 2017), and we will use KCWI time to target the most secure lens candidates (> 70% success, Berghea et al., 2017), simultaneously obtaining CGM measurements and redshifts of the lensing galaxies and their neighbors. These are bright: we expect to obtain high-quality data on 15–20 per night (see, e.g., the exquisite 20 min KCWI exposure of a quadruply-lensed quasar in Rubin et al., 2018b). We will follow up the brightest absorbed sightlines with Keck/HIRES or LBT/PEPSI high-resolution measurements.

C. Strongly lensed galaxies: Lensed galaxy arcs are powerful probes of the CGM of foreground galaxies (Lopez et al., 2018; Péroux et al., 2018; Rubin et al., 2018a). We will observe two types of arcs (Figure 3): single galaxy arcs surrounding individual massive halos and giant arcs created by clusters of galaxies. Both probe the CGM of intervening halos between the observer and the source redshift, useable redshifts $0.3 \lesssim z \lesssim 3$ from the ground. The single galaxy arcs also probe the inner CGM of massive galaxies at $r_{\perp} \sim$3–50 kpc. Both types of arcs provide unique constraints on the CGM given the lengths over which absorption can be measured nearly continuously (10s of kpc). BEARS will include our proprietary KCWI observations of 6 giant arcs (Figure 4), archival MUSE observations for several giant arcs, and proprietary KCWI and archival MUSE data for $\sim$10

[4]PID: 15075; PI: Howk, Co-I's include Tumlinson, Peeples, Lehner, O'Meara, and Bordoloi.

single galaxy arcs. There are *hundreds* of new candidate arcs from machine learning analyses (Diehl et al., 2017, supply > 300). With our guaranteed Keck/KCWI time, we will confirm and measure absorption against > 25 such sources over the first two years of our program.

Telescope access plan: Notre Dame has 10 nights per year on the 2×8.4-m Large Binocular Telescope (LBT) and 5 nights on the twin 10-m Keck telescopes, 1–2 and 0.5–1 nights, respectively, of which we will apply to this program. Collaborator O'Meara will contribute up to 1.5 nights of guaranteed time to the project in his capacity as Keck Observatory Chief Scientist. Collaborators Bordoloi and O'Meara will contribute 2 nights worth of reduced proprietary data.

A majority of the Keck time will use the KCWI IFU spectrograph. KCWI is more sensitive than LRIS for absorption spectroscopy of multiple sight lines (albeit over a more limited wavelength range) and provides the ability to identify simultaneously intervening galaxies. This instrument will be particularly useful for surveying galaxies about the small-angular-separation quasar pairs/quads with existing high-quality HIRES or ESI data. KCWI also offers the distinct advantage that it can observe H I Lyα over $1.9 \leq z \leq 3.5$ (in addition to other tracers at lower redshifts). Our LBT time will target the galaxies associated with the highest-quality absorption line measurements, using the NIR multi-object spectrograph LUCI to trace the galaxy kinematics with, e.g., Hα. Coupled with the ARGOS ground-layer AO correction, this instrument regular achieves $0.25'' - 0.35''$ resolution over a $4'$ field of view. This resolution will therefore be extremely useful for resolved spectroscopy of the absorbing galaxies we will use to understand the CGM/galaxy angular momentum connection.

We will provide back to the community all of our reduced data, as we have in the past, with the HIRES/LRIS/ESI quasar spectra via KODIAQ DR4 and the KCWI and LBT data via BEARS.

D12. Leveraging Observations And Theory With Synthetic Data

Our primary synthetic data products will be mock IFU observations of CGM absorption toward background lensed galaxies (most often, KCWI). We already have the tools to create synthetic HIRES spectra of CGM absorption toward quasars (Peeples et al., 2018). Creating synthetic *JWST* observations of galaxies is funded by our NASA ATP; it will be straightforward to extend these tools to create mock LBT/LUCI data for galaxy kinematics. We will generalize our FOGGIE mock data tools, which were developed and tested against single point-like background sources, to deal with spatially resolved backgrounds. We have already built some of the "2D" code infrastructure to model CGM emission (Corlies et al., 2018). Both intrinsically non-uniform background sources (in the cases of the lensed galaxies) and lensing itself mean that the observed S/N and thus detection limits will necessarily vary spatially, so we will need to add modules for applying the lensing maps, for modeling variable angular sampling (Corlies et al., 2018) and S/N within a field, and for seeing (Simons et al., 2016), neither of which affect point-like background sources[5]

The JHU postdoc will lead the mock data program element. The ND graduate student will use the synthetic data to learn how observed resolution and signal-to-noise propagate to uncertainties in interpretation. For mock CGM data, it is essential to build a map for how cells in the underlying gas are contributing each part of the absorption in the final synthetic data product. A significant infrastructure improvement the JHU postdoc will lead will be adding this functionality to the open-source Trident code (Hummels, Smith, & Silvia, 2017). We use Trident to create mock 1D absorption, but it discards information about *where* that absorption arose, its physical conditions, and kinematics. Thus far, we have kept this careful bookkeeping outside Trident for single-sightlines (Peeples et al., 2018), but for these more complex synthetic data it will be absolutely necessary that we link this information to the observables in more dimensions. *We will provide these updates, along with our full synthetic circumgalactic/IFU generation code, back to the community via Trident.*

[5]Collaborators Corlies and Simons will contribute their expertise to constructing mock-IFU data from simulations.

D13. Broader Impacts: Educational Videos

Our approach for our pedagogical videos is to try to reach two different audiences—teachers and the classroom and the general public—using the simulations as a basis to visualize complex concepts which we will continue in this proposal. In our previous proposal, (1) a video on the basics of spectroscopy in the context of CGM absorption (led by ND and SMC, with synthetic data input from JHU) and in this new proposal, and (2) a video exploring the basics of gravitational lensing (ND) which support the fulfillment of Next Generation Science Standard criteria HS-ESSS1-2. For the general audience, the focus is to highlight interesting current astronomy research and pique overall interest by developing videos describing: (3) the importance of the CGM in galaxy evolution (current grant; JHU and MSU); (4) the cosmic history of quenched galaxies (MSU); (5) supercomputing at the exascale (MSU); (6) on-site observing at Keck (O'Meara, featuring Bordoloi and the ND grad student); (7) interpreting CGM IFU data (JHU&ND). Combining the videos from both NSF grants, we will have a series that, if watched in order, would leave the viewer with an understanding of the underlying methods and concepts driving the research of this program. All materials would be downloadable for public talks given by other astronomers.

D14. You Might Be Wondering...

The plan to get to Enzo-E seems ambitious... Enzo-E has secure funding and a clear development trajectory, and already exhibits the necessary scaling behavior. Several of the solvers necessary for the simulations described here have already been ported. Co-PI O'Shea's main, funded contribution to Enzo-E prior to the start of this grant will be to port the remainder of the modules—particularly the star formation and feedback routines and the AGN feedback algorithms.

What if the simulated AGN feedback / galaxy quenching doesn't "work"? Then we have learned something about the how and why it fails and have better ideas for how to improve it!

Won't you need to secure a lot of computing time for all these simulations? Yes, but we have long experience procuring time on many platforms, and these plans are in line with our previous allocations. We will request time on Stampede2 via XSEDE, Frontera (the Blue Waters replacement) via NSF PRAC, and on Mira, Titan, and Summit via DOE INCITE. In the unlikely event we do not acquire enough computing time to run the full set of 30 halos to $z = 0.5$, we will prioritize a begin fewer halos with priority on the more massive halos, since quenching is a key goal.

Are the FOGGIE simulations converged? It is very difficult to prove convergence in multiphysics cosmological simulations. However, the *observable* quantities of interest in our high-resolution simulations exhibit only minor variations with spatial/mass resolution, particularly compared to these properties in the "standard resolution" simulations. While investigating disk formation and quenching, we will continue to examine the effects of resolution on observables.

Why one big proposal instead of separate observational and theoretical proposals? Our team includes both observers and theorists who can bridge the gap between data and simulations by comparing the two in the observable space. We aim to guide the simulations with a "close read" of the data—and vice versa, which requires regular collaborative contact. Our previous and ongoing collaborations prove this constant communication to be the most fruitful and fastest route to new insights.

Do you really need a postdoc instead of a graduate student at Johns Hopkins? Yes. The postdoc will need to quickly ramp up to running and analyzing a large suite of simulations and must become conversant with observations to make detailed comparisons between data and simulations. Mastery of all this is not a reasonable expectation for a beginning graduate student.

What are your other risks and mitigation strategies? If we cannot hire a qualified postdoc right away, we try again in a later year and phase the project work accordingly (grad students have already been individually identified). Our observational goals are based on archival data and guaranteed time, and thus little risk of not meeting them (except for weather).