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METALS ON THE BH EXPRESS: OXYGEN TRANSPORT IN THE CGM OF SIMULATED MW-MASS GALAXIES

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ABSTRACT

[UNDER CONSTRUCTION] We examine the cosmological hydrodynamic simulation ROMULUS25 (Tremmel et al. 2017) and a suite of zoom-in "genetically modified" (GM) Milky Way-mass galaxies to study the effects of galaxy evolution and SMBH feedback on the CGM. We compare the column densities of OVI in the Milky Way-mass galaxies of ROMULUS25 and compare them with observations from the COS-Halos Survey. We determine that a galaxy's morphology has little effect on the appearance of OVI in its CGM while column densities of OVI are more likely tied to galaxy halo mass. The suite of GM Milky Way-mass galaxies further confirm this result and further examine the effect of AGN feedback on the CGM's OVI. We find that SMBH feedback prescriptions act as the physical mechanism transporting metals out into its host halo thereby significantly impacting the appearance of OVI found in the CGM.

Subject headings: Gas physics – Galaxies: circumgalactic medium – Galaxies: spiral – Galaxies: kinematics and dynamics – Methods: Numerical

1. INTRODUCTION

Things to wordsmith (but also everything)
NOTICE AND FIX ME

The circumgalactic medium (CGM), the extended region of gas surrounding galaxies out to their virial radii, is a rich and vast yet mostly unexplored area of astronomy due to its diffuse, difficult-to-observe nature. Recent observations, due to technological advances like the Cosmic Origins Spectrograph (COS) on the HST, have allowed researchers to finally begin characterizing this mysterious component of all galaxies and find it to be a structurally complex, multiphase medium. (Werk 2012, 2013, 2014, Tumlinson 2011, Also cite Review + others) Examinations like Ford (Ford 2013) which showed that most of the "missing baryons" of galaxies likely resides in this diffuse region imply that the CGM may play a key role in the growth of galaxies and the build up of their disks. Therefore, it is clear that understanding the CGM is a significant component to understanding the complex nature of galaxy evolution and growth.

Several studies have been done to examine the effect of galaxy evolution on the CGM. Tumlinson 2011's COS-Halo observations show a correlation between the column densities of OVI and the specific SFR of their observed galaxy CGMs with higher abundances of OVI around SF galaxies compared to their passive counter parts. Subsequent arguments have been made to understand this result. Oppenheimer 2016 argue that this bimodality arises due to the OVI acting as a proxy for the virial masses of these galaxy halos, as the oxygen in the star forming galaxies are subsequently in the correct virial temperature range to maximize OVI production. Therefore, the more massive galaxies in the COS-Halo sample show less OVI in their CGM due to the intrinsically higher virial temperature of these massive red ellipticals. Other arguments have been made to explain this correlation however, as Suresh 2017 argues that the NOVI abundances in SF galaxies arise due to feedback from the AGN, which can physically sculpt via outflows or heat the CGM to appropriate temperature for ionizing OVI. In both cases, we see the argument for an intrinsic link between the CGM and its host galaxy's evolution.

Since galaxy evolution has been shown to be strongly tied to the evolution of its central supermassive black hole (SMBH) —through relations like the M-σ and the bulge mass-BH mass correlation which indicates that the SMBH and its host galaxy halo *grow together* (Reines 2015, other from "Gebhardt et al. 2000a; Ferrarese & Merritt 2000; Marconi & Hunt 2003; Haring & Rix 2004; Gultekin et al. 2009; McConnell & Ma 2013; Kormendy & Ho 2013, and references therein" from Reines 2015) —it is unsurprising that the AGN is thought to also leave its marks on the CGM. However, the direct mechanisms by which the AGN impacts the CGM most readily are still hotly debated.

AGN are thought to effect the CGM in a number of ways. Feedback from the active SMBH may inject energy into the surrounding material, raising temperatures, and ionizing metals in the gas **[CITE]**. Outflows of gas from the AGN may also physically push gas out of the galaxy (some of which may end up falling back into the galaxy as part of the "recycling" of the CGM **[CITE; CGM review]**), enriching CGM gas with metals from the center of the galaxy, and furthermore enriching the IGM as gas is expelled from the galaxy. Since observations are limited to spectroscopic analysis (which can help us understand the abundances and structure of ions in the CGM), simulations are necessary to examine the physics driving the multiphase nature of the CGM.

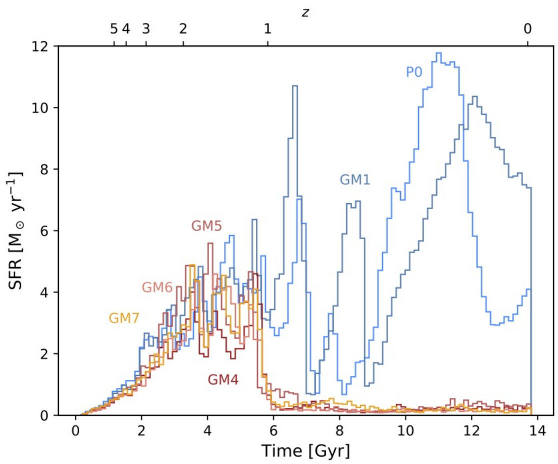

FIG. 1.— The star formation histories for each of our 12 GM galaxies.

Simulators have long been examining the underlying physics of AGN activity in galaxies; however, examining these effects in the diffuse region of the CGM is still a fairly new expedition. We continue this trek of new discovery utilizing a cutting-edge suite of simulations: the cosmological volume, ROMULUS25 (Tremmel et al. 2017) and 12 individual genetically modified Milky-Way (MW) mass galaxies (Roth et al. 2016; Pontzen et al. 2017) with and without the implementation of advanced BH physics (Tremmel et al. 2015). We'll use these simulations in tandem to further examine the roles that galactic evolution and AGN feedback play in characterizing where OVI lives within the CGM of MW-mass galaxies.

2. SIMULATION PARAMETERS

ROMULUS25 and our suite of GM galaxies were run with an ΛCDM cosmology from the most recent Planck collaboration utilizing $\sigma_0 = 0.3086$, $\alpha = 0.6914$, h = 0.67, $\sigma_8 = 0.77$ and have Plummer equivalent force softening lengths of 250 pc.

Both the ROMULUS25 and the zoom-in GM simulations were run using the smoothed particle hydrodynamics (SPH) N-body tree code, Charm N-body GrAvity solver [ChaNGa][](Menon et al. 2015). ChaNGa includes the same models for a cosmic UV background, star formation, 'blastwave' SN feedback, and **metal line cooling** as previously used in GASOLINE (Wadsley et al. 2004, 2008; Stinson et al. 2006; Shen et al. 2010). ChaNGa includes an improved SPH formalism which includes a geometric density approach in the force expression: $(P_i + P_j)/(\rho_i \rho_j)$ instead of $P_i/\rho_i^2 + P_j/\rho_j^2$ where P_i and ρ_i are the particle's pressure and density, respectively. This update to the hydrodynamic treatment includes thermal diffusion (Shen et al. 2010) and reduces artificial surface tension allowing for better resolution of fluid instabilities (Ritchie & Thomas 2001; Menon et al. 2015; Governato et al. 2015). Additional improvements have been made to the BH formation, accretion, and feedback models as well an improved prescription for dynamical friction (Tremmel et al. 2015, 2017).

For simulating the cosmic reionization energy, both simulations enact a UV background at z 9 using the formula of Haardt & Madau (2012). Some recent papers **[CITE]** have raised concerns that this UV background is too strong resulting in [**look over this background and get citation**]. However, since our primary concern is the abundance of OVI which is considered to be collisionally ionized rather than photoionized [**CITE**], our choice of UV background should not affect our results.

2.1. *Romulus 25 Cosmological Volume*

To give a statistical background to our calculations, we examine a ROMULUS25, a cosmological volume simulation including galaxies within the mass range 10^{10} —10^{13} [**CHECK THIS**]. While both simulated galaxy suites have comparable force resolution, ROMULUS25 has a mass resolution of 3.4×10^5 $M_\odot$ and 2.1×10^5 $M_\odot$ for DM and gas particles, respectively.

2.2. *Genetically Modified Galaxies - h243*

[**CONFIRM ALL DEETS WITH ANDREW**] For our GM simulations, an initial uniform-volume, 50 h^{-1} Mpc on a side, DM-only cosmological volume was simulated from which a Milky Way-mass halo at z=0, h243, was selected as our "Patient 0" and re-simulated at a higher resolution, with and without black hole physics.

The Black Hole Case: At z = 0, our "Patient 0" (hereafter P0) of the galaxy simulation h243 has a final main halo mass of $\sim 1.07 \times 10^{12}$, virial radius of 269 kpc, and total gas and stellar masses of 1.09×10^{11} and 5.71×10^{10}, respectively (Table 1).

Mass resolution: DM: 1.4 10^5 Msun gas: 2.1 10^5 Msun The DM field is simulated at twice the gas linear resolution to reduce noise in the potential near the galactic center (Pontzen et al. 2017) and more accurately trace black hole dynamics (Tremmel et al. 2015).

Patient zero has an incoming satellite at z = 1 which we shrink prior to its merger with the main halo for our subsequent genetic modification, GM1 and GM4. GM5 and GM6 are genetic modifications of GM4 where the satellite mass is maintained and the main halo's final mass is increased and decreased respectively. [**Make a table of satellite masses/modifications**]

3. SIMULATION ANALYSIS

Individual halos in the ROMOULUS25 cosmological volume and in the individual zoom-in GMs are extracted using the Amiga Halo Finder (AHF) (Knollmann & Knebe 2009) and central SMBH positions and velocities are defined relative to the center position and inner 1 kpc center-of-mass velocity of their host halo, respectively. From ROMULUS, we specifically examine Milky Way-mass halos which are defined as halos between 5×10^{11} and 2×10^{12} $M_\odot$ and are at least twice a virial radii from their nearest neighbor (to exclude any satellites). All GMs are isolated zoom-in galaxies with a minor merger **(q = 0.05)** at z=0.

The CGM of each individual galaxy halo is defined as the mass enclosed from 10 kpc from the center position out to a virial radius defined as the radius at which 200 times the critical density, ρ_c, where $\rho/\rho_c = 200$.

Column densities of OVI are calculated using the analysis software Pynbody [**PONTZEN 2013**]. Oxygen is traced throughout the time of the simulation and OVI ion fractions are calculated using a CLOUDY model [**Hennawi, Pockaska, Stinson?**].

TABLE 1
Gas+BH Simulation Details

Sim	Total Halo Mass ($M_\odot$)	Total Gas Mass ($M_\odot$)	Total Stellar Mass ($M_\odot$)	CGM Gas Mass ($M_\odot$)	R_{vir} (kpc)	T_{vir} (K)
P0	1.07×10^{12}	1.09×10^{11}	5.71×10^{10}	1.02×10^{11}	268.9	5.12×10^5
GM1	1.07×10^{12}	1.01×10^{11}	6.43×10^{10}	9.18×10^{10}	269.2	5.12×10^5
GM4	7.76×10^{11}	6.36×10^{10}	1.04×10^{10}	6.35×10^{10}	241.7	4.14×10^5
GM5	8.93×10^{11}	9.11×10^{10}	1.41×10^{10}	9.09×10^{10}	253.3	4.54×10^5
GM6	6.81×10^{11}	5.77×10^{10}	1.13×10^{10}	5.75×10^{10}	231.4	3.79×10^5

To further understand the effects of the AGN in our galaxies, we reran all six of the original GM galaxies (including Patient 0) without any of the BH physics prescriptions. [See Table X with parameters of NO BH runs]

4. RESULTS

Figure 2 shows the phase diagrams for all 12 of our zoom-in GM galaxies. Between the star forming galaxies and quenched galaxies there isn't a considerable difference. It's also important to not that comparing the six phase diagrams of the galaxies with BH physics and the six without BHs are not significantly different either.

Figure 3 shows that ChaNGa well simulating OVI in the CGM as compared to COS-Halo data. [Figure 3 **FIX LEGEND, ADD PASSIVE GALAXIES**]

We see this is true for all Milky Way mass galaxies in the Romulus simulation regardless of whether they are star forming or quenched. [Figure 3]

Result 1: The morphological evolution of the galaxy doesn't correlate with the evolution of the CGM. Instead, it appears that the mass of the galaxy, and connectedly its virial Temperature [Table 1], plays a more significant role in determining the amount of OVI seen in the CGM. (Cite Oppenheimer in Discussion)

In addition to providing evidence for our initial result, the ROMULUS simulation give **cosmological credence** to our suite of GM galaxies. We see the same confirmation of our result within Patient 0 and its GMs, which include two star forming galaxies and four quenched galaxies. [Figure 4] (Also here: We leave the examination of the quenching mechanisms affecting this galaxy and its GMs to a future paper.) As mentioned, the benefits of the individual zoom-in galaxies include the ability to remove or adjust the physical parameters affecting our galaxies to test different theoretical models (which would be too computationally expensive to do with a large volume like ROMULUS.)

When we examine the secondary suite of GM simulations (without BH physics), we see a significant change in the amount of OVI present in the CGM. [Figure 5]. We examine the temperature, mass, density, and metallicity of the CGM to investigate the cause of this decrease in OVI. [Figure]

The difference between the CGMs of these two cases appears to come directly from the change in metallicity due to the lack of black hole activity. [Figure] We examine the metallicity of the disk to look for further clues about how the lack of AGN activity is affecting the galaxy.

The metallicity profile of the gas in the disk (Figure) shows a build up of metals in the center of the galaxies without BH physics. Without the AGN, metals are not being propagated into the CGM but instead remaining locked in the gas of the disk.

It appears that the AGN plays a significant role in physically driving the metals out of the disk and into the outer regions of the CGM.

Result 1: OVI as a Tracer for Virial Temperature of the Halo

The combined, consistent results of the cosmological ROMULUS and our 6 GM galaxies (which include BH physics [**think of a good short hand for distinguishing between BH GMs and Non)**) imply a mechanism by which column densities of OVI are optimized by the virial temperature of the CGMs host galaxy, rather than any affect by the evolution of a disk. Their phase diagrams also lack significant difference in their overall morphology, except where more gas is clearly present in the higher mass galaxies. Therefore, we surmise that the difference in the CGM are less motivated by the quenching of a galaxy but rather these differences are primarily driven by the virial temperature of the galaxy.

These results are consistent with Oppenheimer et. al. 2016 who used a suite of EAGLE simulated galaxies and found the bimodality of OVI column densities (further discussed in [Tumlinson 2011]) in star forming and quenched galaxies. They argue that the star forming galaxies (10^{11} - 10^{12}), which were found to have a higher fraction of OVI, were at the right virial temperature to maximize OVI production, while their quenched galaxies (10^{12} - 10^{13}) had high enough virial temperatures such that the dominant ionization state was not OVI but rather OVII or above. Oppenheimer et. al. 2016 argues that the OVI content was not a tracer of star formation directly, but rather a more direct thermometer for the temperature of the halo.

We note that the quenched galaxies in our sample are smaller in mass than our star forming galaxies, unlike those in Oppenheimer, explaining the lack of bimodality that we observe. While all the GMs are in the mass range to have virial temperatures which optimize OVI, we further examine the ROMULUS simulation's higher mass, passive galaxies to see if the bimodality appears. [Figure 8] We see that as the mass of the galaxy Oppenheimer et al. (2016). We determine that the OVI still provides a direct thermometer for the temperature of the halo.

Furthermore, examining galaxies with masses larger than our MW-mass GMs ($>2 \times 10^{12}$) from the R25 suite, we see that the column densities of OVI decrease as the ionization peak of OVI is surpassed by these halos. Since the virial temperature is higher, the oxygen is likely to be ionized to a higher ionizations state (OVII or OVII), which we show is the case in Figure 8. **NEED TO INCLUDE OVII PLOT**

Result 2: AGN as driver for metals in the CGM

Our result that the AGN acts a physical driver for

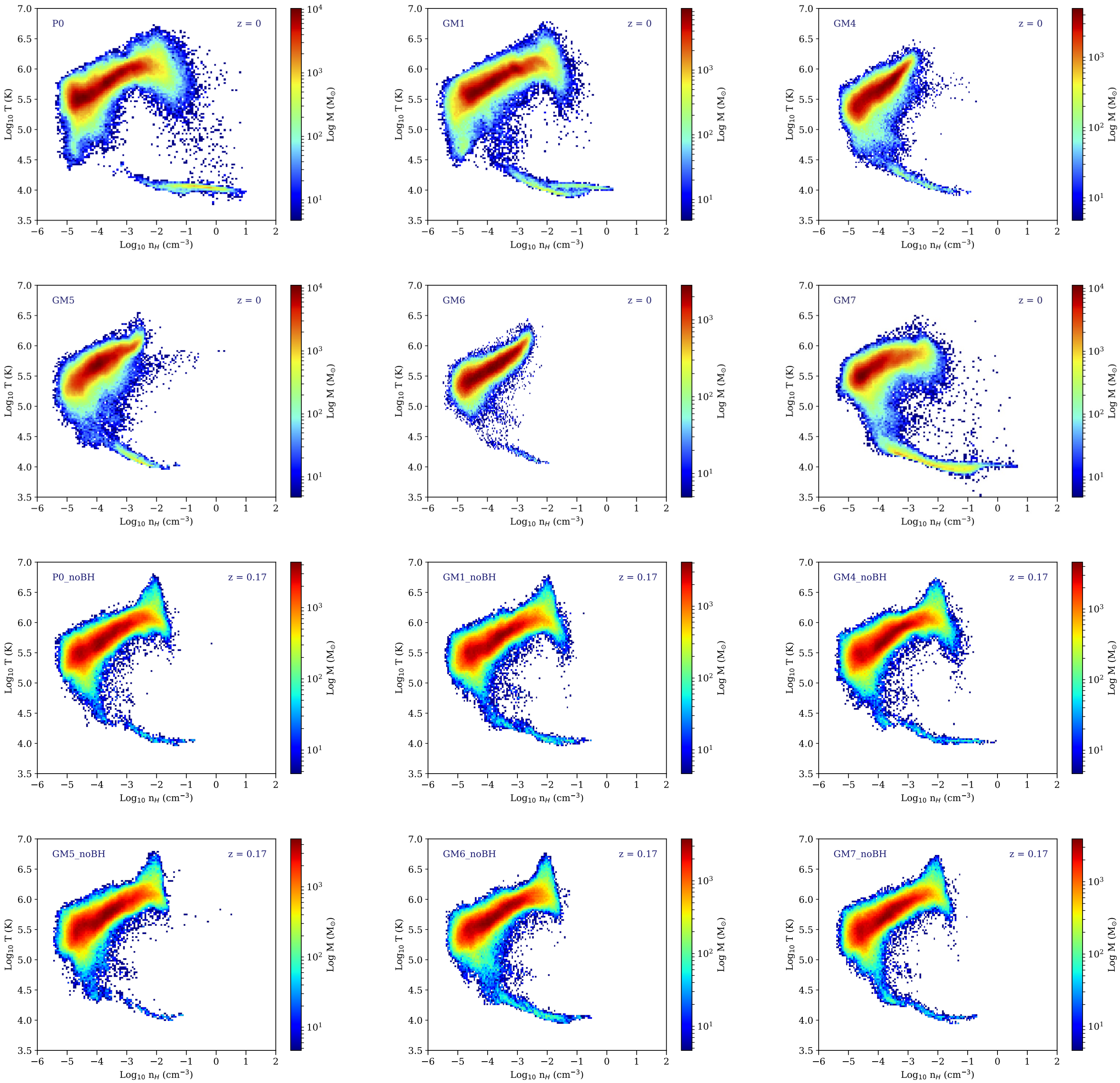

FIG. 2.— Phase diagrams of the temperature and density of our 12 GM galaxies, upper 6 with and lower 6 without black hole physics included.

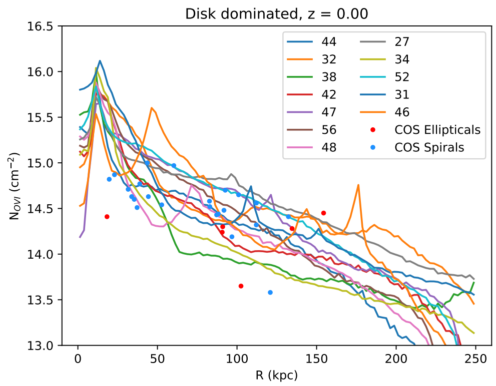

FIG. 3.— Column densities of OVI as a function of radius for all Milky Way mass halos in the Romulus simulation. **Remake: Need to differentiate between SF and quenched**

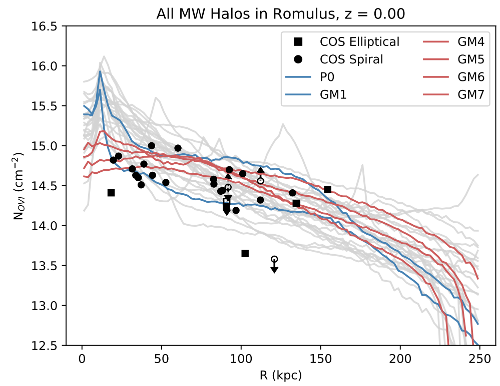

FIG. 4.— Column density profiles of OVI in our 26 ROMULUS and 12 GM galaxies. Grey lines are as in Figure 3, and describe our 26 MW-mass ROMULUS galaxies. Blue solid lines describe our two star forming galaxies, P0 and GM1. GM4-7, our passive galaxies, are in solid red. Black circles indicate

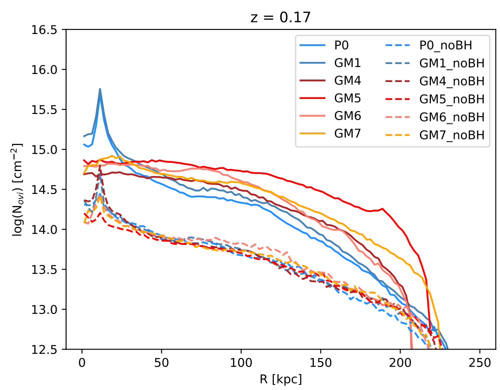

FIG. 5.— Column density profiles of OVI in our 12 GM galaxies. Solid and dashed lines represent galaxies with and without BH physics, respectively. P0 and GM1, our two star forming galaxies are colored as light blue and dark blue, respectively. Our quenched galaxies, GM4-7 are labeled in shades of red.

metals in the CGM has interesting consequences. Previous studies have examined the effect of heating on the CGM as the AGNs energy input may put the gas into phases which optimize the production of OVI. (Suresh et al. 2017) Others have proposed that the feedback from AGN may physically drive outflows of gas out of the galaxy, resulting in a lower density CGM and therefore lower densities of OVI. Neither of these cases are what we see. *Instead, we see a suite of CGM which rely on the AGN for the propagation of metal mass (but not total gas mass) into the outer galaxy and OVI columns which depend on the virial temperature of the galaxy.*

5. CONCLUSION

Acknowledge some cool peeps.

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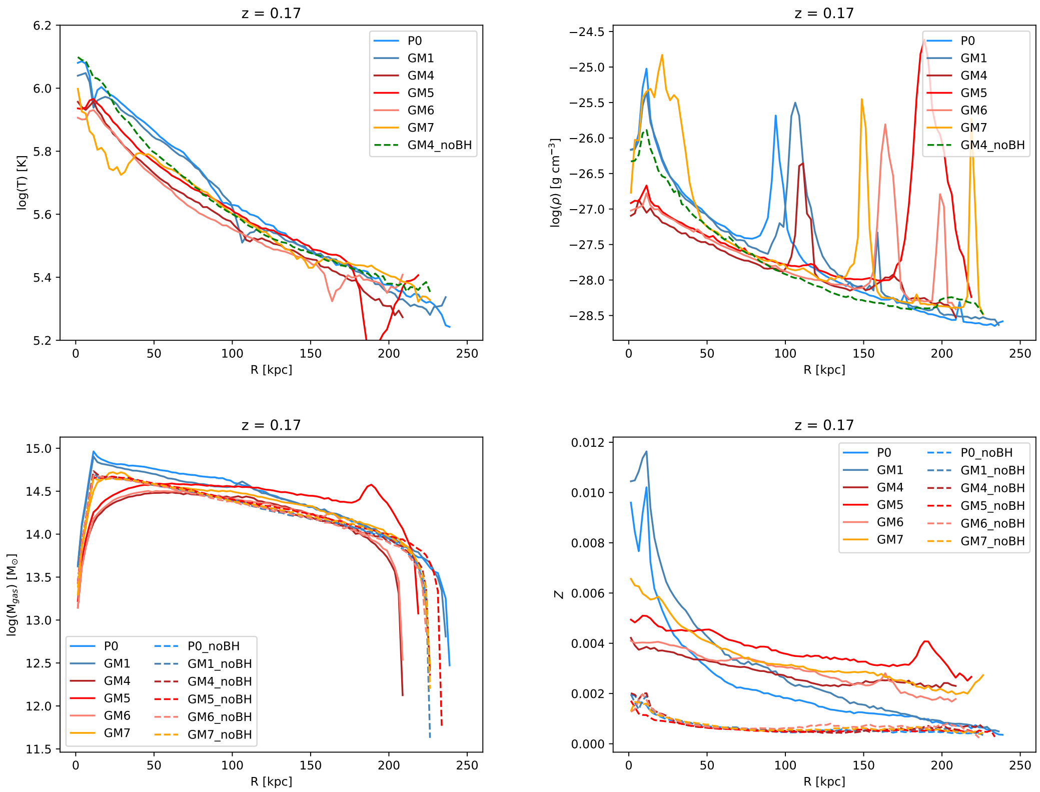

FIG. 6.— Temperature, Total Mass, Total Density, and Metallicity profiles of the CGM of our 12 GM galaxies (with and without BH physics). Colors and linestyles as in Figure.

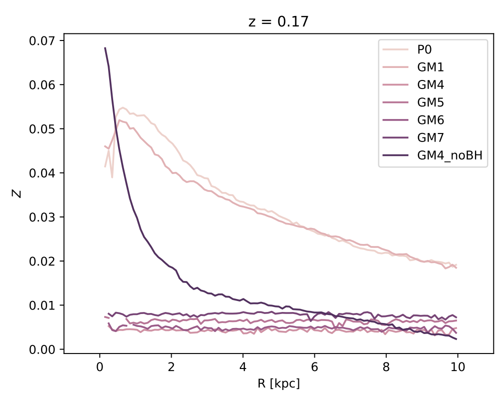

FIG. 7.— [Fix colors] Metallicity profile of the gas within the disk of our 12 GM galaxies. Colors and line styles as in Figure . Without the black hole physics, metals remain trapped near the center of the disk with no mechanism to propagate out into the CGM

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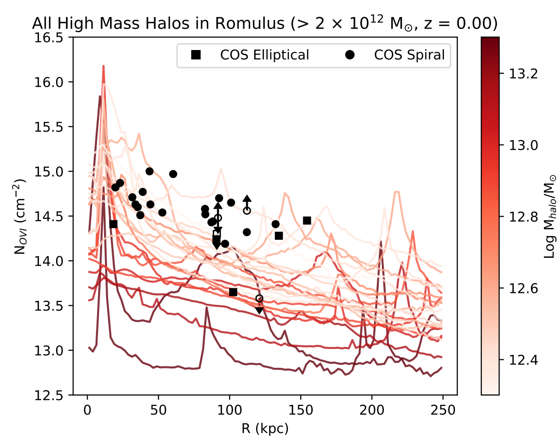

FIG. 8.— Profiles of the column densities of OVI for High Mass galaxies in the ROMULUS simulation. The color bar describes total mass of the halo within the virial radius. As describes in Oppenheimer et al. (2016), NOVI values are lower for more massive, passive galaxies due to the higher virial temperatures they reach which ionize oxygen to higher states, such as OVII.

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