Gaseous Halos of Simulated MW-like Galaxies

Bhavya Pardasani

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1 Abstract

Satellite galaxies interact hydrodynamically with their more massive host galaxy, which causes them to be stripped of their gas and subsequently cease forming stars. To better understand how satellites are impacted by the host environment, we have characterized the gaseous halos of 14 Milky Way-like galaxies from the FIRE simulations over time in order to model the role of the host halo in quenching satellite galaxies. We have quantified the density of the host halo environment with respect to both distance from the host and galactocentric latitude. At present day (z=0), the density decreases with increasing distance from the host as well as above and below the disk (at higher latitudes). We find that most of the hot halo gas profiles are well fit by a broken power law function. At earlier times (z=0.16 to z=1.76 i.e. 2 Gyr to 10 Gyr ago), the density in the inner regions of some of the host halos was enhanced relative to z=0 (present day), implying that a satellite that fell in earlier or approached these galaxies along the disk (at lower latitudes) will experience more ram-pressure stripping and be more efficiently quenched.

2 Introduction

Satellite galaxies are dwarf galaxies that are gravitationally bound to the host galaxy, and orbit within 300 kpc from it. Their presence in the host environment causes them to interact with the gas of the host hydrodynamically. A consequence of this hydrodynamic interaction is quenching - cessation of star formation - of these satellite galaxies. The host environment quenches the satellite galaxies by stripping off their cold gas while they are infalling into the host environment.

Our galaxy, the Milky Way is in a paired host system with the Andromeda. This paired system and the satellite galaxies bound to both hosts make up the Local Group. My project targets simulated MW-like galaxies, i.e. galaxies that have mass, composition and structure similar to the Milky Way. It is expected for MW-like galaxies to have a quenched fraction

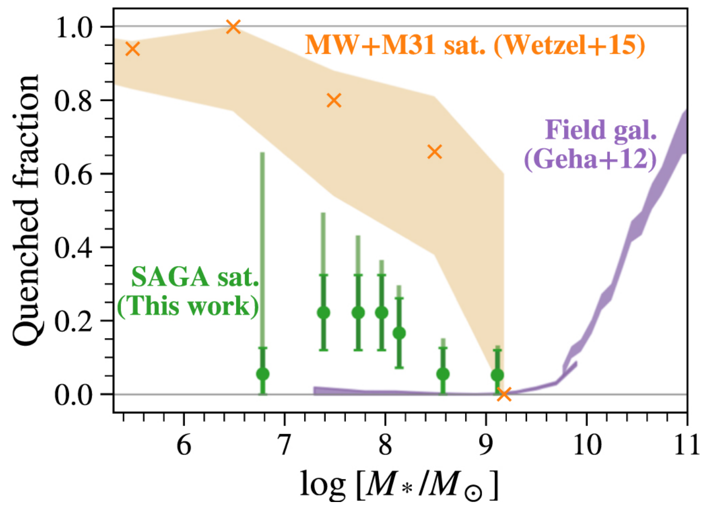

Figure 1: The SAGA survey plot from Mao et al. (2021). We can see that the green scatter is significantly lower than the orange scatter. This is unexpected as SAGA investigated MW-like galaxies but the quenched fraction observed is not in a similar range as the Milky Way.

similar to the Milky Way's, however, the Satellites Around Galactic Analogs (SAGA) survey (Figure 1) found a significantly lower quenched fraction of satellites for 36 nearby isolated MW-mass galaxies (Mao et al., 2021). This could possibly be because SAGA investigated only isolated galaxies while the Milky Way is in a paired environment. A natural explanation could, thus, be that the difference is due to the paired vs isolated environment. However, the paired vs isolated nature of the host environment is actually less correlated with higher quenched fractions than the host halo gas mass in the FIRE simulations (see Figure 2).

FIRE simulations are cosmological hydrodynamic zoom-in simulations consisting of gas, star and dark matter particles. Each gas/star particle in these simulations has a mass of 7100 $M_\odot$. To place this in context, the Milky Way's stellar disk alone weighs around $5\times10^{10} M_\odot$, implying that it is resolved with around 7 million particles, and in total there are around $\sim$ 100 million particles in each simulation. I am analysing 14 simulated MW-like galaxies - 8 isolated and 6 paired hosts - which are surrounded by populations of satellite dwarf galaxies (Wetzel et al., 2016; Garrison-Kimmel et al., 2019; Samuel et al., 2020).

My research project primarily focuses on characterizing the gaseous halos of simulated MW-like galaxies, and modeling the role of the host halo in quenching the satellite galaxies. Despite the fact that gas makes up less than fifteen percent of the Universe, my analysis exclusively works with the gas particles as the ram pressure stripping experienced by satellite galaxies is due to hydrodynamic interactions between these particles. I started my analysis with m12i, a simulated MW-like galaxy, and then extended my analysis pipeline to 13 other paired and isolated host galaxies from the FIRE simulations.

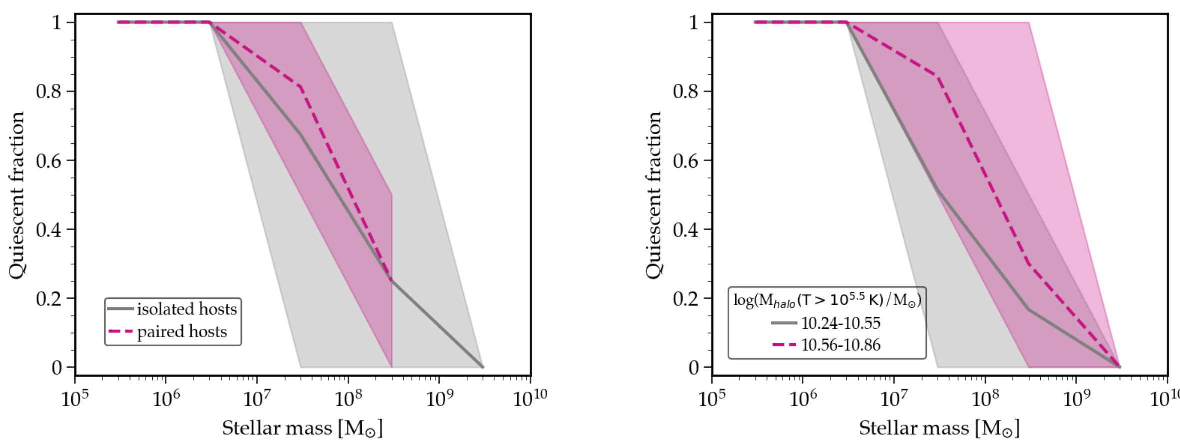

Figure 2: *Left:* This plot from Samuel et al. in prep shows that even though the line representing paired hosts depicts a higher quenched fraction than the line representing isolated hosts, the scatters for both the hosts do not have a significant difference. Thus, the difference in quenched fraction is not due to the paired versus isolated nature of the host environment. *Right:* This plot from Samuel et al. in prep shows that halo gas mass of the host environment plays a very significant role in the quenching offered to the infalling satellites. The higher the hot halo gas mass, the higher is the quenched fraction of the host galaxy.

The host environment usually consists of an inner halo which is mostly made up of cold gas (T $<10^4$ K), and an outer halo that consists hot gas (T$>10^4$ K). The majority of cold gas in the host environment have been recently stripped off from a satellite. The ram-pressure experienced by an infalling satellite is given by the equation $P \approx \rho v^2$. My analysis determines the number density at different regions in the host halo over the last 12 billion years in order to model the role of the host halo gas in quenching satellites.

3 Results

After loading in the particle data at a particular redshift for the host/hosts I am working with, I retrieved the total distance from the host for each particle. For all my radial profile plots, I selected particles in a region of 30-300 kpc from the host as most of the ram-pressure stripping takes place in this region, and most of the gas particles are concentrated in a virial radius of 300 kpc. The y-axis depicts the density in $Atoms/cm^3$ and the x-axis plots the distance from the host in kpc or the latitude in degrees. I have plotted the mean number density in each 10 kpc bin. The non-uniformity of the upper scatter in Figure 4 tells us that the density in individual 10 kpc bins is not uniform throughout the bin. This gives us an idea of the extent of unevenness in the number density of the host halo environment. I have utilized `Astropy` fitting to fit the median densities, and to get a better physical interpretation of the various regions inside the host halo. The functional form of the fitting curve is `Astropy`'s `BrokenPowerLaw1D`, which is shown in Equation 1. The table containing the fitting parameters is given at the end of this section in Table 1.

$$f(x) = \begin{cases} A(x/x_{break})^{-\alpha_1} & x < x_{break} \\ A(x/x_{break})^{-\alpha_2} & x > x_{break} \end{cases} \quad (1)$$

The phase diagram in Figure 3 shows that most of the halo gas particles are concentrated in an adiabatic region at higher temperatures (top left), particularly at T$>10^5$ K (Samuel et al. in prep). Though the gas can heat and cool in the simulations, it is mostly neutral hydrogen so it does not have efficient cooling pathways to cool below 10^4 K, leading to an isothermal horizontal band in this region. Taking the phase diagrams from Samuel et al. in prep as inspiration, I have plotted the data using different temperature regions in Figure 4. The temperature regions I used for my plots, in particular, are T$>10^{5.5}$ K and T$<10^{5.5}$ K. Using $10^{5.5}$ K as the temperature cut instead of 10^5 K seems to work better with most of the hosts as I obtained better fits while retaining a majority of the mass of the halo, hence I chose it to be the main temperature cut for the rest of my analysis.

The radial profile for the cold halo gas in Figure 4 has more uneven scatter than the radial profile for hot halo gas. This unevenness can be attributed to the cold satellite gas particles that were not completely masked out in the code despite our effort to mask out up to ten times the half-mass radius. We chose $10^{5.5}$ K as the temperature cut after trying out a

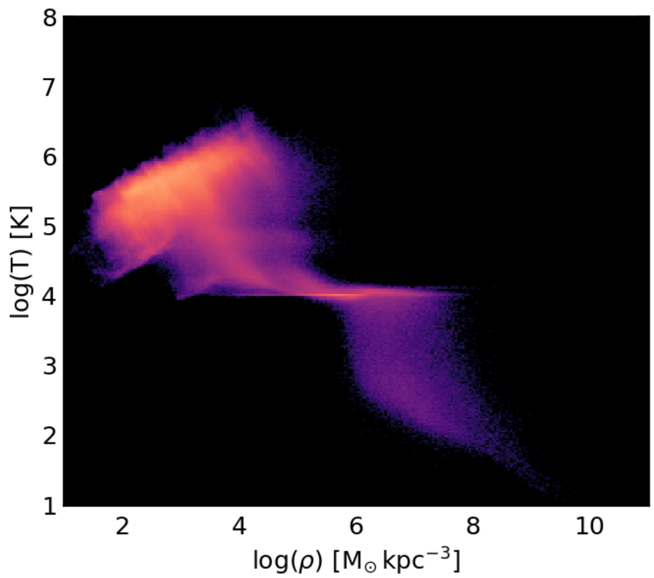

Figure 3: This is a phase diagram of halo gas of m12i from Samuel et al. in prep. The y-axis plots the log of the temperature and the x-axis represents the mass density of individual gas particle. We notice a constant line at 10^4 representing isothermal gas as these gas particles have not met the conditions required to cool down further. The lighter regions represent higher number of particles, which tells us that majority of the particles are present at T$>10^5$ K implying that an infalling galaxy experiences majority of its ram-pressure stripping due to the particles in the temperature region T$>10^5$ K.

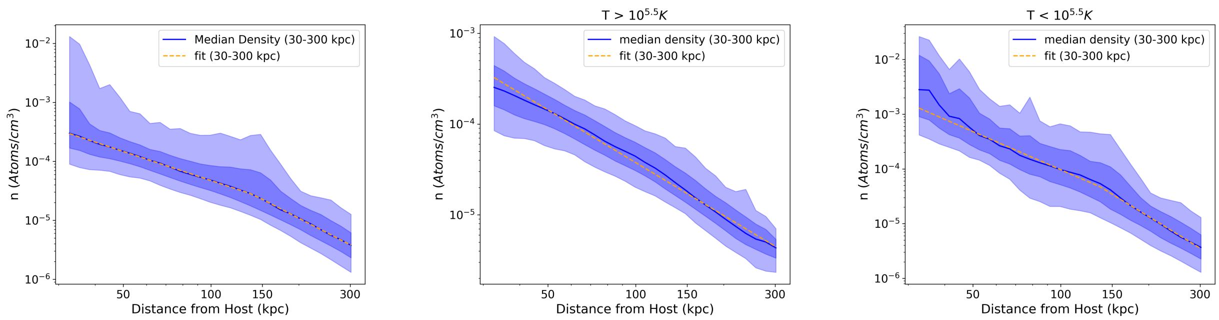

Figure 4: *Left:* Radial Profile of m12i with respect to distance from the host at z=0. The orange dashed line is the best-fit line and its functional form is broken power law (Equation 1). The darker/inner scatter is the 68th percentile while the lighter/outer scatter is 95th percentile. Median number density in individual 10 kpc bins has been plotted. The non-uniform upper scatter tells us that the number density is not uniform in each 10 kpc bins as well. *Middle:* Radial Profile of m12i with respect to distance from the host at z=0 for temperature greater than $10^{5.5}$ K. *Right:* Radial Profile of m12i with respect to distance from the host at z=0 for temperature less than $10^{5.5}$ K.

lot of temperature regions and realizing that switching from scipy to astropy is what gives a better physical interpretation for fit parameters. The smoother profiles of the hot gas halos are also more easily fit. Henceforth, we will target the hot halo gas as that temperature region has the most number of particles, implying that it is the hot gas particles that are responsible for most of the ram-pressure stripping of the satellite gas.

To study the evolution of MW-like galaxies, and subsequently the Milky Way, I plotted the radial density profile of the m12i with respect to distance from the host over time from z=1.76 to z=0 i.e. 10 Gyr ago to present day in Figure 5. We observe in this figure that the density decreases generally as we approach z=0, but this trend is at 50 kpc as the density at z=0.64 and z=1.04 is higher than the density at z=1.76. This unexpected break in trend can be because the galaxy was heavily accreting at z=0.64 and z=1.04. Thus, this plot lets us conclude that the ram-pressure stripping experienced by an infalling satellite galaxy will vary depending on when it falls into the host halo environment.

After doing all this analysis on the m12i, I attempted to expand my analysis pipeline to the other hosts in the FIRE simulation. The radial profile plots of the other hosts were significantly choppier than the plots I obtained for the m12i. To study how these hosts differ from each other and the m12i, I made a plot (Figure 6) of the mean number densities (in individual 10 kpc bins) as a function of distance from the host using the same method I used for radial profile plots of m12i.

Until now, we have focused our analysis on examining the density of the Circumgalactic

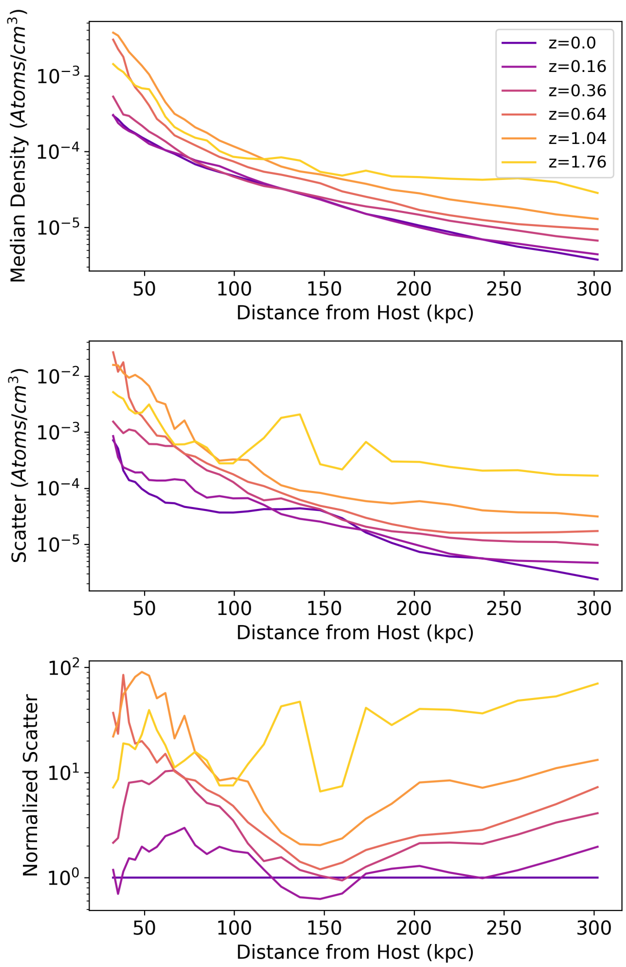

Figure 5: Evolution of radial profile of m12i with respect to distance from the host over time from z=1.76 to z=0. The top panel is a plot of median density, the middle panel is a plot of the difference of the upper 68^{th} percentile scatter and median density, while the bottom panel is the second plot normalized to z=0. As we approach z=0, the density in the outer halo decreases monotonically due to the expansion of the universe. Thus, the ram-pressure stripping offered by the host environment of m12i has decreased over time.

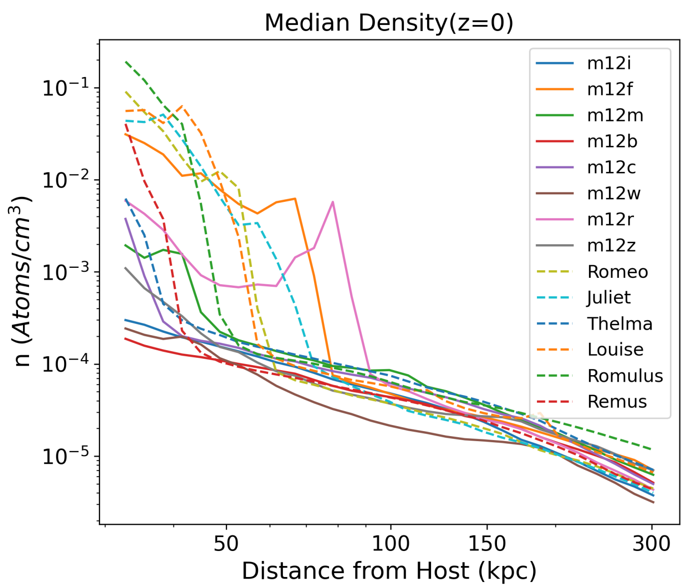

Figure 6: This figure plots number density of all the hosts I am working with with respect to distance from the host at z=0. Paired hosts are shown with dashed lines and isolated hosts are solid lines. It gives us a better picture of the choppiness observed in various hosts and different ranges of number density, thus, allowing us to compare the hosts as well.

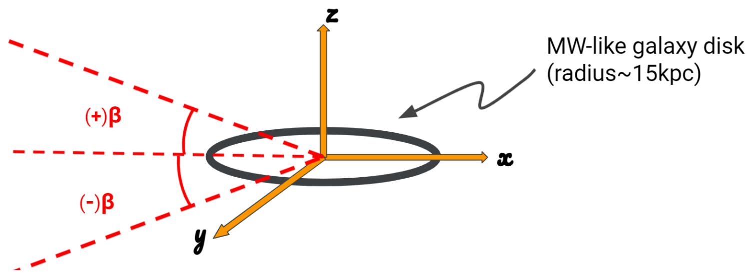

Figure 7: This is a schematic diagram depicting the galactocentric latitude. Here, my code calculates β for each particle based on its position relative to the host and then chooses particles in a given range of β. See Equation 2 for the formula used to calculate β.

Medium (CGM) solely as a function of distance from the host, however, density also likely varies as a function of galactocentric latitude (β). In Figure 7 we illustrate how β is measured using a Cartesian coordinate system centered on the host, with the z axis aligned with the minor axis of the host disk (see Equation 2 for the formula). We predicted that higher number density would be concentrated at low latitudes, and the number density would taper off as we go to higher latitudes.

$$\beta = \arctan\left(\frac{z^2}{\sqrt{x^2 + y^2}}\right) \tag{2}$$

We can see in Figure 8 that the number density is higher at lower latitudes and decreases as we approach the extremes. This general trend is broken when the line representing distance cut 100-150 kpc has an unexpected bump in the 25-50 degree region, a bump so big that it reaches a density equal to or higher than the density at 50-100 kpc in the same azimuthal range. This might be due to the presence of stripped satellite gas that was not masked out completely from the data. We have employed four distance bins in this plot to study how latitude differs at different distances from the host. As expected, the further we go from the host, the number density with respect to latitude decreases i.e. the number density in the 30-50 kpc region is more than all the subsequent distance cuts and so on.

In conclusion, satellites that experience close passages/pericenters at low latitudes will be more effectively stripped of their gas versus satellites that have pericenters at high latitudes. Moreover, this characteristic is also experiencing an evolution over time i.e. the ram-pressure stripping offered by the host environment of m12i with respect to latitude has decreased over time.

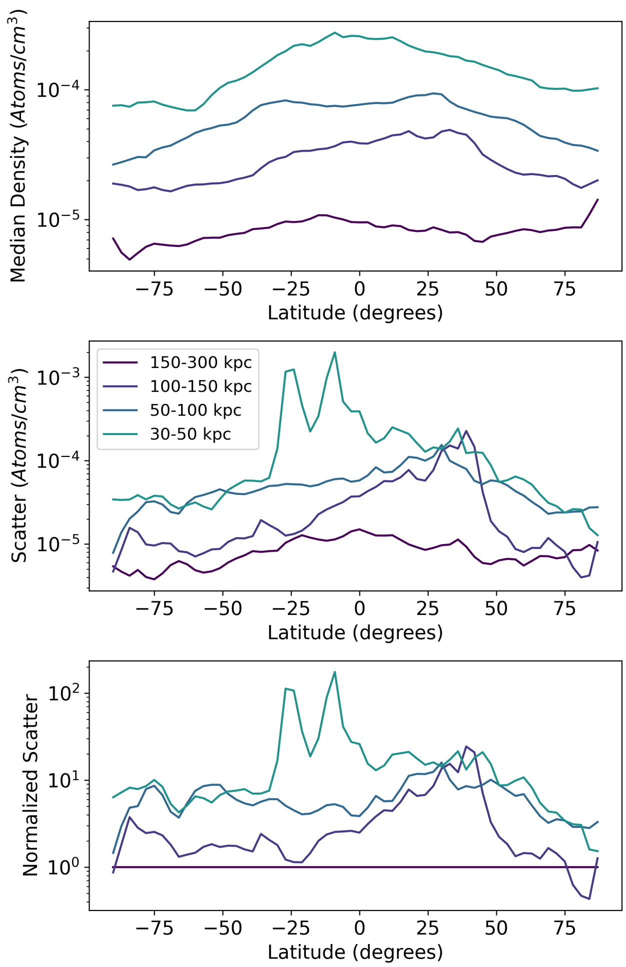

Figure 8: Gas density of m12i with respect to latitude at z=0 at various distance cuts. The y-axis of the top panel shows median density, the second panel shows the difference of the upper 68^{th} percentile scatter and median density, and the third panel is the second subplot normalized to z=0. The median density decreases as we approach lower latitude regions (-25 degrees to 25 degrees) and this trend is mostly followed. The density decreases the further we move away from the host.

Table 1: Above $10^{5.5}$ K Fitting Parameters

Hosts	Amplitude	x_break	Alpha_1	Alpha_2
m12i	0.3	0.94	1.0	1.93
m12f	0.0	90.7	1.02	1.6
m12m	0.0	155.81	1.41	2.6
m12b	0.0	167.22	1.28	2.45
m12c	0.0	133.86	1.07	2.47
m12w	0.06	0.37	1.0	1.43
m12r	0.04	0.52	1.0	1.39
m12z	0.0	148.83	0.67	1.36
Romeo	0.02	2.3	0.65	1.68
Juliet	0.01	3.04	1.0	1.7
Thelma	0.0	143.45	1.34	2.45
Louise	0.0	167.82	1.45	2.38
Romulus	0.0	77.17	1.01	1.48
Remus	0.0	23.59	1.2	1.66

3.1 Fitting parameters

The fitting parameters of the hot gas of the host halo are given in Table 1. x_{break} is the distance from the host where the median density curve changes its functional form, hence BrokenPowerLaw1D fits the portion before x_{break} and after x_{break} separately. As you can tell from the values in the x_{break} column of Table 1, the fitting is much better for hosts like m12m, m12b, m12c etc. while the x_{break} values for hosts like m12w and m12r are not quite reasonable in comparison. I have not included the fitting parameters for the cold gas as the fits obtained seemed to fail due to the presence of satellite gas in the data. Since our primary objective is to study the host halo environment, the fits obtained for hot gas seemed more valuable as they correspond to the host halo gas exclusively.

4 Conclusion

My project examines the total halo gas mass of 14 hosts, and analyses the number density as a function of both distance from the host and latitude. I have also investigated how my analysis evolves with time i.e. from z=1.76 (13 Gyrs ago) to z=0 (present day).

The plots of density as a function of distance help us conclude that the noisy nature of cold halo plots causes them to not be as well fit by the BrokenPowerLaw1D as the hot halo plots are. The cold halo gas is subdominant to the hot halo gas in terms of the overall mass of the host halo, therefore, its radial profile is too noisy to be fit well with a smooth fitting curve. Hence, we are not going to attempt fitting the cold halo gas plots anymore.

From our analysis of gas density with respect to latitude, we can conclude that the number density is higher at lower latitudes, which implies that a satellite approaching at lower latitudes will experience more ram-pressure stripping as compared to an approaching satellite at higher latitudes.

The time evolution plots with respect to distance and latitude tell us that the number density of the host halo environment has generally decreased as we approach z=0 (present day). There are a few breaks in this trend but they can be attributed to the fact that the galaxy might have been heavily accreting at that time.

5 Future Directions

The FIRE simulations have around 240 satellite galaxies around MW-like hosts, which we can compare against observations of true MW satellites. My work can help us determine the ram-pressure that will be experienced by an infalling satellite galaxy in the respective host environments. I aim to look at the ram-pressure stripping offered to these galaxies statistically by studying the hosts environments across all 14 MW-like hosts. Studying the host environment will make it easier to determine how much ram-pressure will be offered by it to any satellite galaxy falling into its halo rather than studying the satellites individually. These results can also aid us in studying the evolution of the host galaxies over time, and learning more about the Milky Way and the Local Group since the galaxies I am studying are MW-like galaxies.

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