Cloud Formation in a Cosmological Context and Implications for Absorption-Selected Galaxies

Kyle R. Stewart[1], James S. Bullock[1], Tobias Kaufmann[2], Elizabeth Barton[1], Ariyeh H. Maller[3], Lucio Mayer[2], Jürg Diemand[4], Piero Madau[4], James Wadsley[5]

[1]*Center for Cosmology, Department of Physics and Astronomy, The University of California at Irvine, Irvine, CA, 92697, USA*
[2]*Institute for Theoretical Physics, University of Zurich, Winterhurerstrasse 190, Zurich, CH-8057, Switzerland*
[3]*Department of Physics, New York City College of Technology, 300 Jay St., Brooklyn, NY 11201, USA*
[4]*Department of Astronomy & Astrophysics, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA*
[5]*Department of Physics and Astronomy, McMaster University, Main Street West, Hamilton L8S 4M1, Canada*

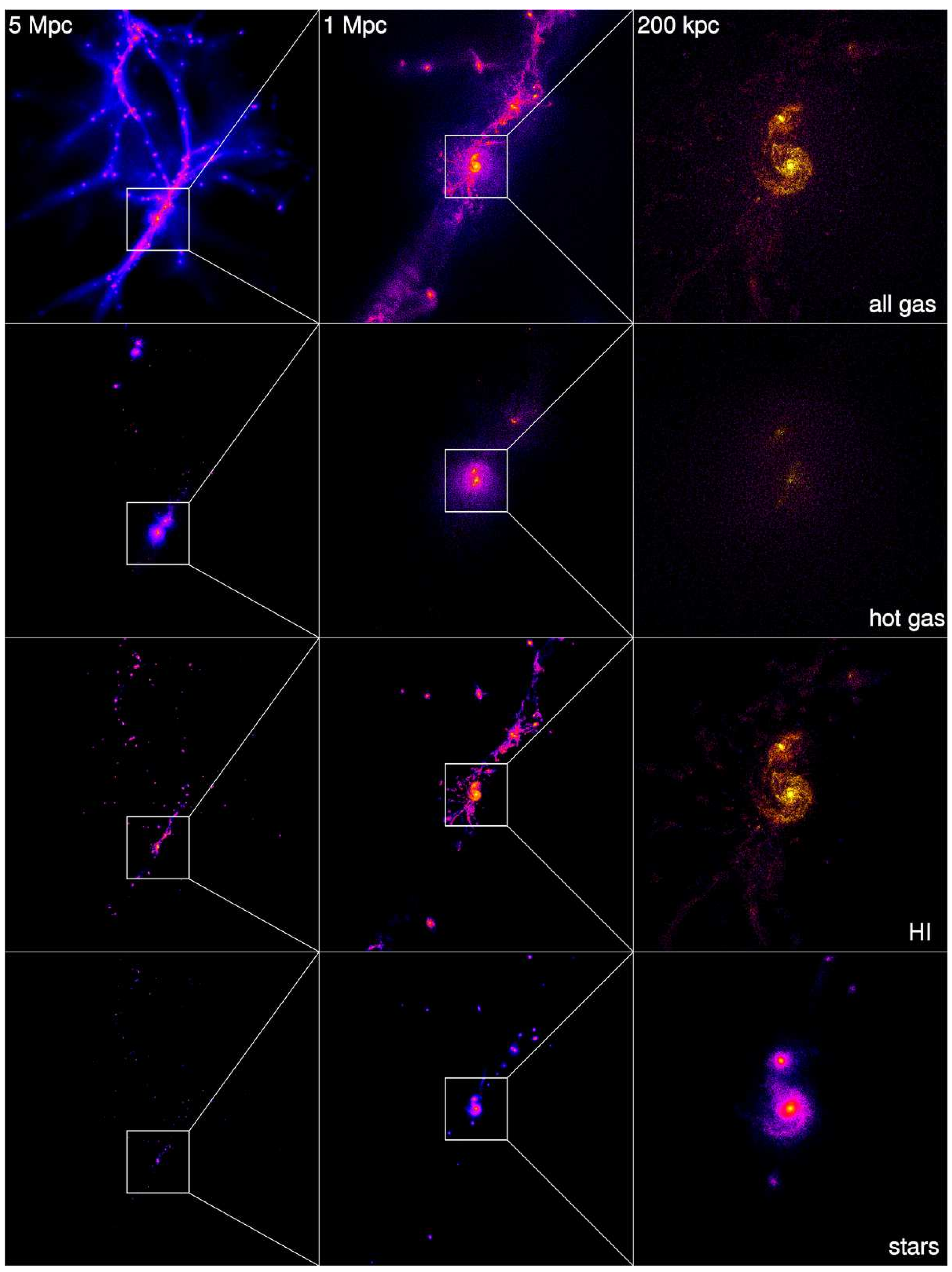
Abstract

The extended gaseous halos of galaxies provide a valuable means of probing recent accretion activity, from major mergers to smooth gas inflow along filaments. We explore the evolution of the extended gaseous halo of a Milky Way-size galaxy using a high resolution hydrodynamic simulation that implements the same initial conditions used in the "Via Lactea II" simulation. We observe the formation of a clumpy gaseous halo around the galaxy, leading to a significant covering fraction of HI within 50 kpc ($30-50\%$ for $z > 0.8$). In detail, this covering fraction is a strong function of recent gas accretion, either via cold flows at high redshift, gas-rich mergers, or the infall of pressure-supported gas clouds.

Motivation

In Milky Way-sized dark matter halos, cold gas and stars in the galaxy itself only accounts for $\sim 20\%$ of the baryonic content implied by the universal baryon fraction. A variety of observations, such as local X-ray absorbers, high velocity clouds, and MgII absorption systems along quasar lines of sight, all suggest a reservoir of extended gas in the halos of galaxies, out to ~ 100 kpc. In order to fully understand galaxy formation, it is important to know the role of this extended gas. Is this gas that has been ejected from the galaxy, or is it infalling gas? Does the gas originate from cold flows? Gas-rich mergers? Cooling cloud fragmentation? We aim to use our simulation as a comparative tool for observations, in order to help constrain the mechanism by which gas is accreted onto galaxies.

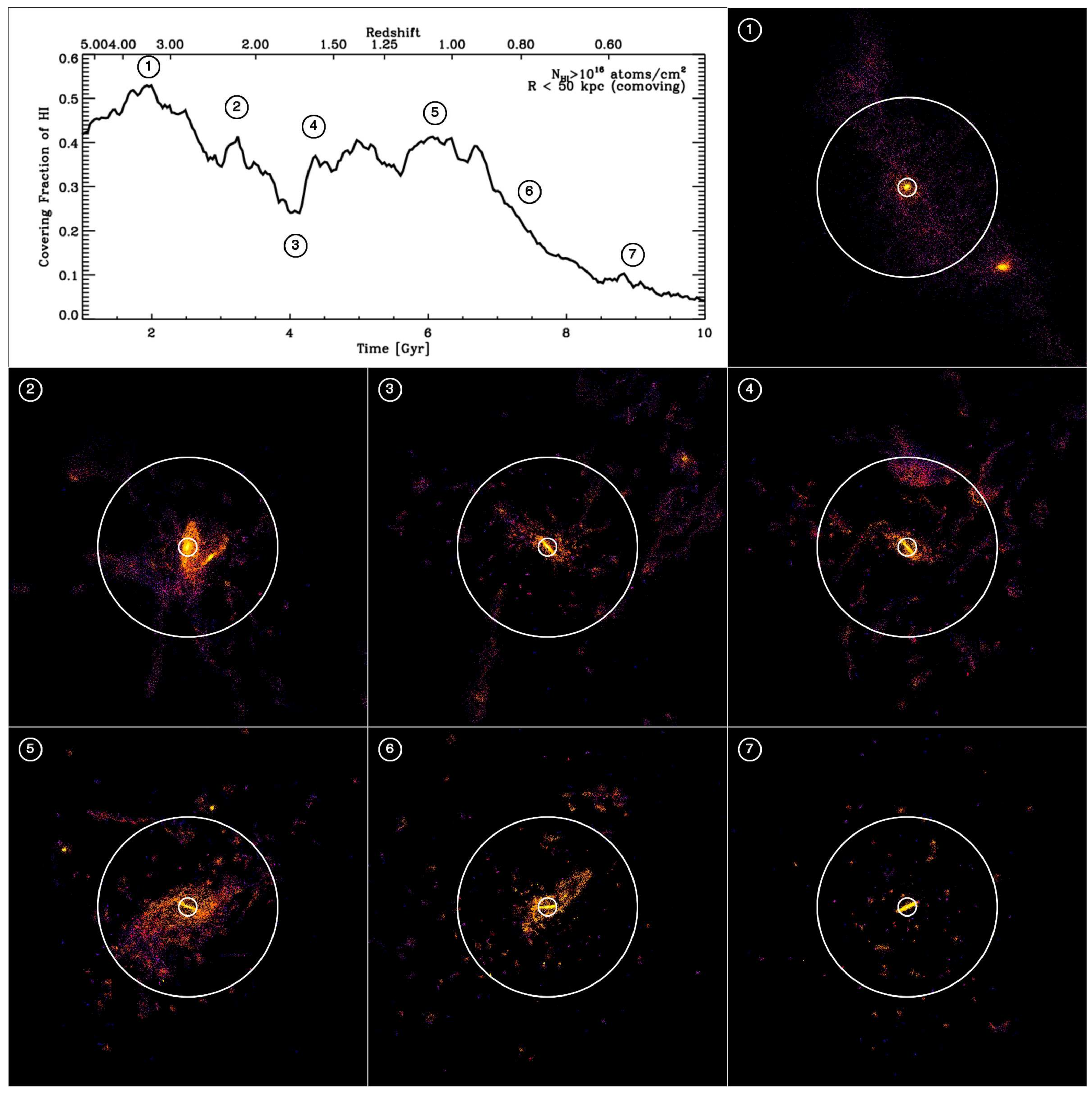
The Simulation



Our "VL2gas" simulation, shown above, implements the same initial conditions from the Via Lactea II simulation (halo mass $M_{\rm vir}(z=0) \sim 2\times10^{12} M_{\odot}$). We implement the "zoom in" technique to properly account for large-scale tidal torques [Katz & White(1993)]. The simulation uses the smooth particle hydrodynamics (SPH) code GASOLINE [Wadsley et. al(2004)] to treat the behavior of gas. There are no strong winds, or AGN feedback in this simulation. The star formation and the "blastwave feedback" prescriptions [Stinson et. al(2006)], as well as the cosmic UV field [Haardt & Madau(1996)] we adopt are the same prescriptions implemented in recent simulations that have shown great success in producing realistic disk-type galaxies [e.g., Governato et. al (2008)].

In the highest resolution region, the masses per particle of our simulation are: $(m_{\rm dark}, m_{\rm gas}, m_{\rm star}) = (3.7, 3.4, 1.0)\times 10^5 M_{\odot}$. The peak force resolution and sph smoothing length are both 332 pc. In the image shown above, from left to right, panel widths correspond to 5 Mpc, 1 Mpc, and 200 kpc (comoving). The white squares in each panel show the "zoom in" area of the panel to the right. Top to bottom, images show 3-d density of: all gas, hot ($T > 500,000K$) gas, cold gas (neutral hydrogen), and stars. The images above show the galaxy about to experience a major merger at $z \sim 1.5$.

Results: Covering Fraction of HI



Covering fraction of neutral hydrogen as a function of time. The numbered circles in the upper-left panel each correspond to one of the seven images of the central galaxy shown in the other panels. The width of each image is 200 kpc (comoving), with the white circles representing a radius of 50 kpc (the area used to compute the covering fraction) and 5 kpc (we ignore gas inside this inner radius in computing the covering fraction, because we are interested in extended halo gas, not the galaxy itself). The covering fraction is computed by sampling ~ 200 regularly-spaced lines of sight through the simulation at a radius $R < 50$ kpc, measuring the total column density of HI (within 500 km/s of the central galaxy) along each line of sight. Any line of sight with $N_{\rm HI} > 10^{16}$ atoms/cm^2 is considered "covered" with absorbing gas. This procedure is done for 3 perpendicular orientations of the galaxy, to get an averaged covering fraction per snapshot.

Implications

For the purposes of discussion, the seven panels in the figure above will be referenced as (1-7).

- At high redshift ($z > 2$), galaxies have high covering fractions primarily due to cold flows (1).
- Major mergers increase the covering fraction significantly while both galaxies are distinct, but the dynamical timescales for such interactions are short, and most of the gas associated with the merger ends up in the central galaxy, not the gaseous halo (2,3).
- Minor mergers at high redshift, which contain significant quantities of gas, but few stars, are stripped of gas during the interaction. This gas is not tightly bound to the infalling galaxy. As a result, the interaction leaves much of this gas in the outer halo of the galaxy, to slowly fall back into the galaxy over ~ 2 Gyr timescales (4,5).
- At intermediate redshift ($z \sim 1$), most infalling gas takes the form of pressure-confined clouds, gently "raining" onto the central galaxy (5). Some of this gas is newly infalling material, but a significant amount was associated with past gas-rich mergers.
- Galaxy-galaxy interactions serve to "stir-up" the extended gaseous halo of this galaxy, keeping the gas from settling into the galaxy itself. Once galaxy-galaxy interactions become less frequent at later times, the gas settles into the galactic disk, and begins to form stars. This causes a dramatic decline in the covering fraction, as the reservoir of gas within the galaxy's extended halo is consumed in star formation (6,7).

Note, especially for this last point, that this particular galaxy used the same initial conditions as Via Lactea II, whose merger history was specifically chosen to be quiescent at $z < 1$. It is unclear if the behavoir of this particular galaxy's covering fraction at $z < 1$ is indicative of "average" galaxies, as most galaxies will have at least one merger of mass ratio $> 1/10$ since $z = 1$ [Stewart et. al(2008)]. In addition, our feedback prescriptions included *no* strong outflows or AGN feedback. These mechanisms may help to remove gas from the central galaxy, despositing it in the extended halo, which may increase the covering fraction and delay gas consumption. Thus, our results may be thought of as a conservative lower limit on the "true" covering fraction.

References

[Haardt & Madau(1996)] Haardt, F. & Madau, P. 1996, ApJ, 461, 20

[Katz & White(1993)] Katz, N. & White, S. D. M. 1993, ApJ, 412, 455

[Stewart et. al(2008)] Stewart et. al. 2008, ApJ, 683, 597

[Stinson et. al(2006)] Stinson et. al. 2006, MNRAS, 373, 1074

[Wadsley et. al(2004)] Wadsley et. al. 2004, New Astronomy, 9, 137

Contact information: Kyle R. Stewart, 4120 Frederick Reines Hall, Department of Physics and Astronomy, University of California, Irvine, CA 92882 – Email: *stewartk@uci.edu*; Web: *http://www.physics.uci.edu/ stewartk/*