

# NIHAO VII: Predictions for the galactic baryon budget in dwarf to Milky Way mass haloes

Liang Wang<sup>1,3\*</sup>, Aaron A. Dutton<sup>2,3</sup>, Gregory S. Stinson<sup>3</sup>, Andrea V. Macciò<sup>2,3</sup>,  
Thales Gutcke<sup>3</sup>, Xi Kang<sup>1</sup>

<sup>1</sup>*Purple Mountain Observatory, the Partner Group of MPI für Astronomie, 2 West Beijing Road, Nanjing 210008, China*

<sup>2</sup>*New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE*

<sup>3</sup>*Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany*

to be submitted to MNRAS

## ABSTRACT

We use the NIHAO galaxy formation simulations to make predictions for the baryonic budget in present day galaxies ranging from dwarf ( $M_{200} \sim 10^{10} M_{\odot}$ ) to Milky Way ( $M_{200} \sim 10^{12} M_{\odot}$ ) masses. The sample is made of 88 independent high resolution cosmological zoom-in simulations. NIHAO galaxies reproduce key properties of observed galaxies, such as the stellar mass vs halo mass and cold gas vs stellar mass relations. Thus they make plausible predictions for the baryon budget. We present the mass fractions of stars, cold gas ( $T < 10^4 \text{K}$ ), cool gas ( $10^4 < T < 10^5 \text{K}$ ), warm-hot gas ( $10^5 < T < 10^7 \text{K}$ ), and hot gas ( $T > 10^7 \text{K}$ ), inside the virial radius,  $R_{200}$ . Compared to the predicted baryon mass, using the dark halo mass and the universal baryon fraction,  $f_b \equiv \Omega_b/\Omega_m = 0.15$ , we find that all of our haloes are missing baryons. The missing mass been relocated past 2 virial radii, and **cool gas dominates corona at low mass ( $M_{200} \lesssim 3 \times 10^{11} M_{\odot}$ ) while the warm-hot gas dominates at high mass ( $M_{200} \gtrsim 3 \times 10^{11} M_{\odot}$ )**. Haloes of mass  $M_{200} \sim 10^{10} M_{\odot}$  are missing  $\sim 90\%$  of their baryons. More massive haloes ( $M_{200} \sim 10^{12} M_{\odot}$ ) retain a higher fraction of their baryons, with  $\sim 30\%$  missing, consistent with recent observational estimates. **Moreover, these more massive haloes reproduce the observed fraction of cold, warm-hot and hot gas, the fraction of cool gas we predict is significant lower than the observation from COS-HALOs, but agree with the analysis of Stern et al. (2016).**

**Key words:** galaxies: evolution – galaxies: formation – galaxies: dwarf – galaxies: spiral – methods: numerical – cosmology: theory

## 1 INTRODUCTION

Cosmic structure formation has redistributed the baryons from a nearly uniformly distributed plasma into a variety of states, including stars, stellar remnants, cold (atomic and molecular) gas, and hot (ionized) gas. The theories of galaxy formation can predict the amount of mass in these different states, which can in turn be tested by observational constraints.

On cosmological scales, the ratio between the total baryonic and gravitating mass is measured to be  $f_b \equiv \Omega_b/\Omega_m \simeq 0.15$  (The Planck Collaboration 2014). However, the cold baryonic mass density implied by several galaxy baryon estimates (**mainly about stars and cold gas**) is only 3-8% of the big bang nucleosynthesis expectation (Per-

sic & Salucci 1992; Fukugita et al. 1998; Bell et al. 2003; McGaugh et al. 2010). The majority of the cosmic baryons are thought to be in the form of hot gas around or between galaxies (Cen & Ostriker 1999). Until recently only a fraction of these baryons had been detected (Bregman 2007; Shull et al. 2012). This discrepancy is referred to as the “missing baryon problem”. Several theoretical studies with cosmological simulations have constrained the phase of the potential reservoirs of the missing baryons **in intergalactic medium (IGM), and find a large fraction of the baryons with low density and high temperature resides between the galaxies** (Yoshida et al. 2005; He et al. 2005; Davé et al. 2010; Zhu et al. 2011; Haider et al. 2016).

The circum galactic medium (CGM) is **another** major potential reservoir of the missing baryons. HI and metal absorption lines are expected to signpost such diffuse baryonic content. HI is mainly from gas with temperature  $T \sim 10^4 \text{K}$

\* wangliang@pmo.ac.cn

so that it is able to detect cold gas in the CGM. Meanwhile, theoretical work has predicted that a substantial portion of the CGM is in the warm or hot phase with temperature  $T > 10^{4.5}$  K. Gas enters this phase through photoionization, accretion shocks or shocks caused by galactic winds (van de Voort & Schaye 2012). Such dilute halo gas is at  $T \sim 10^{4.5-7}$  K, so the detection is dominated by metal lines, e.g. OVI. Recent advances in the detection of gas in the CGM have come from the COS survey (Tumlinson et al. 2011, 2013; Thom et al. 2012; Werk et al. 2012, 2013). On the scale of Milky Way mass haloes  $M_{200} \sim 10^{12} M_{\odot}$  a significant amount of warm ( $10^4 < T < 10^7$  K) gas has been detected (Werk et al. 2014), accounting for 33-88% of the baryon budget. In the future such observations will be extended to a wider range of halo masses. A number of large volume cosmological simulations (Ford et al. 2013, 2015; Suresh et al. 2015; Oppenheimer et al. 2016) and zoom-in cosmological simulations (Stinson et al. 2012; Hummels et al. 2013; Shull 2014) have given predictions for the HI and OVI absorption line. Gutcke et al. (2016) compared the column density profile of OVI and HI in the CGM of galaxies from the NIHAO (Wang et al. 2015) cosmological hydrodynamical simulation suite with observations, studied the covering fraction of dense HI, looked at the shape of the CGM and its chemical composition. The conclusion shows **the simulation can reproduce the observational covering fraction and column density profile of cool HI well, and echo observed OVI column density trend. As commonly in other simulations, however, the column density of OVI is lower and the extent of optically thick HI is smaller than observed.**

The physical properties of the CGM has been shown to be able to test feedback models (Sharma et al. 2012; Marasco et al. 2013). Davé (2009) predicted galactic halo baryon fractions of galaxies with halo masses ranging from  $10^{11} M_{\odot}$  to  $10^{13} M_{\odot}$  using cosmological hydrodynamical simulations with a well-constrained model for galactic outflows. They found that, without the outflow model, the baryon fraction inside the virial radius is roughly the cosmic baryonic fraction, but with the outflow model, the baryon fraction is increasingly suppressed in lower mass haloes. By comparing results at  $z = 3$  and  $z = 0$ , they showed that large haloes remove their baryons at early times while small haloes lose baryons more recently due to the wind material taking longer to return to low-mass galaxies than high-mass galaxies. Muratov et al. (2015) showed similar results that the gas and baryon fractions are lower at lower redshift, after powerful outflows at intermediate redshift  $z \approx 0.5 - 2$  remove a large amount of gas from the halo. van de Voort et al. (2016) found baryon fraction and gas fraction are reduced compared to the cosmic mean baryon fraction, and low mass haloes reduce larger since feedback can easily expel gas from it, which is consistent with existing observation. Sokolowska et al. (2016) studied the halo gas of three Milky way-sized galaxies using cosmological zoom-in simulations. They found that most of missing baryons actually resides in warm-hot and hot gas which contribute to 80% of the total gas reservoir. The recovered baryon fraction within 3 virial radii is 90%. The warm-hot medium is sensitive to the feedback model so that a reliable spatial mapping of the warm-hot medium will provide a stringent test for feedback models.

In this paper we make predictions for the baryonic budget for stars, cold, warm and hot gas in and around the virial radius of haloes of mass ranging from  $M_{200} \sim 10^{10} M_{\odot}$  to  $10^{12} M_{\odot}$ . We use a sample of 88 zoom-in galaxy formation simulations from the NIHAO project. Reproducing the stellar mass content in dark matter haloes both today and in the past has been a formidable challenge for cosmological galaxy formation simulations (Weinmann et al. 2012; Hopkins et al. 2014). Even the latest state-of-the art simulations have trouble: the ILLUSTRIS simulation (Vogelsberger et al. 2014) strongly overpredicts the stellar masses in dwarf galaxy haloes ( $M_{200} \lesssim 10^{11} M_{\odot}$ ), while the EAGLE simulations (Schaye et al. 2015) underpredict the peak of the star formation efficiency in halos of mass  $M_{200} \sim 10^{12} M_{\odot}$ . In contrast, the NIHAO galaxies are consistent with the stellar mass vs halo mass relations from halo abundance matching since redshift  $z \sim 4$  (Wang et al. 2015), the galaxy star formation rate vs stellar mass relation since  $z \sim 4$  (Wang et al. 2015), and the cold gas mass vs stellar mass relation at  $z \sim 0$  (Stinson et al. 2015). Therefore, the simulations make plausible predictions for the mass fractions and physical locations of the warm and hot gas components. We find that all the haloes contain less baryons than expected according to the cosmic baryonic fraction, but the missing fraction is strongly mass dependent.

This paper is organized as follows: The cosmological hydrodynamical simulations including star formation and feedback are briefly described in §2; In §3 we present the results including the baryonic budget, baryon distribution, and a comparison with observations; §4 gives a summary of our results.

## 2 SIMULATIONS

In this study we use simulations from the NIHAO (Numerical Investigation of a Hundred Astrophysical Objects) project (Wang et al. 2015). The initial conditions are created to keep the same numerical resolution across the whole mass range with typically a million dark matter particles inside the virial radius of the target halo at redshift  $z = 0$ . The halos to be re-simulated at higher resolution with baryons have been extracted from 3 different pure N-body simulations with a box size of 60, 20 and 15  $h^{-1}$  Mpc respectively. We adopted the latest compilation of cosmological parameters from the Planck satellite (the Planck Collaboration et al. 2014). More information on the collisionless parent simulations, **the force softenings and particle masses for the highest refinement level for each simulation** and sample selection can be found in Dutton & Macciò (2014) and Wang et al. (2015).

We use the SPH hydrodynamics code GASOLINE (Wadsley et al. 2004), with a revised treatment of hydrodynamics as described in Keller et al. (2014). The code includes a subgrid model for turbulent mixing of metal and energy (Wadsley et al. 2008), heating and cooling include photoelectric heating of dust grains, ultraviolet (UV) heating and ionization and cooling due to hydrogen, helium and metals (Shen et al. 2010).

the star formation and feedback modeling follows what was used in the MaGICC simulations (Stinson et al. 2013). **The gas converts into stars according to the**

Kennicutt-Schmidt Law when it satisfies a temperature and density threshold. Stars feed both metals and energy back into the ISM gas surrounding the region where they formed. SN feedback is implemented using the blastwave formalism described in Stinson et al. (2006). Pre-SN feedback is an effort to consider radiation energy from massive stars which is an important complementary to physical model for stellar feedback. Heating is introduced immediately after massive stars form based on how much star light is radiated. Our simulations use thermal feedback to provide pressure support and increase gas temperature above the star formation threshold to decrease star formation. There are two small changes in NIHAO simulations: The change in number of neighbors and the new combination of softening length and particle mass increases the threshold for star formation from  $9.3$  to  $10.3 \text{ cm}^{-3}$ , the increase of pre-SN feedback efficiency  $\epsilon_{\text{ESF}}$ , from  $0.1$  to  $0.13$ . The more detail on star formation and feedback modeling can be found in Wang et al. (2015).

### 3 BARYON BUDGET

We define the fiducial baryonic mass as:

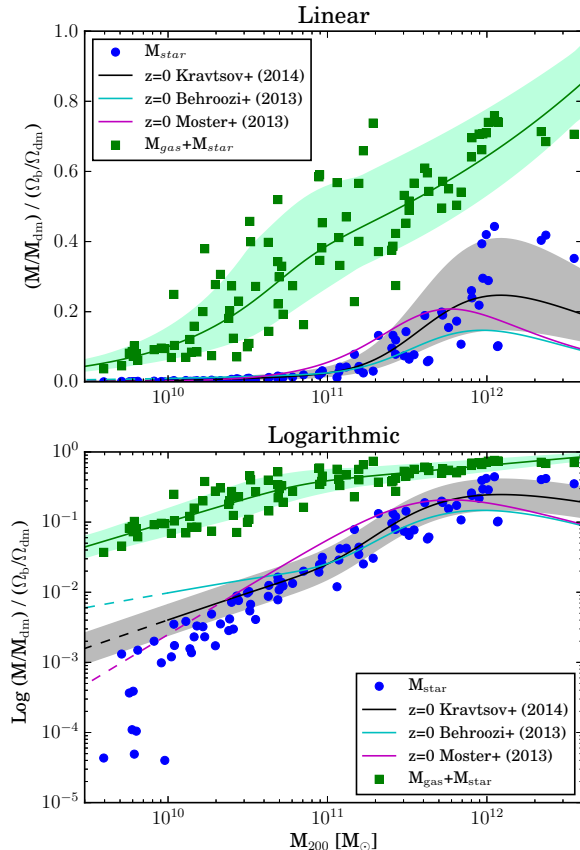
$$M_b \equiv M_b(R_{200}) = \frac{f_b}{1 - f_b} M_{\text{dm}}(R_{200}) \quad (1)$$

where the  $M_{\text{dm}}$  is the total dark matter mass of the halo, and the  $f_b = \Omega_b/\Omega_m \sim 0.15$  is the cosmic baryon fraction (the ratio between baryon density and mass density including baryonic mass plus dark matter), so that  $M_b$  would be the baryonic mass inside the virial radius if the baryons followed the dark matter closely.

Fig. 1 shows the ratio between the mass of each baryon component inside the virial radius to the fiducial baryonic mass for the most massive galaxy in each zoom-in region. We present the fractions of total stellar mass (blue points), and the total baryonic mass including stellar mass plus gas mass (green points). For the stellar mass fraction we also show the relations from the halo abundance matching (Moster et al. 2013; Behroozi et al. 2013; Kravtsov et al. 2014). The grey area is the one sigma scatter around the mean value from Kravtsov et al. (2014). Fig. 1 shows that all haloes in our study contain less than the universal fraction of baryons. The upper panel uses a linear y-axis scale, which highlights the large amount of baryons that are missing, especially in low mass haloes. The logarithmic scale in the lower panel highlights the power-law nature of the relations.

The trends of each component fraction are similar, in that the fractions are relatively low in low mass haloes, and increase as the halo mass increases. The main difference between the different components is the slope, with the baryonic mass fraction having a shallower slope than the stellar mass fraction. This is because in low mass haloes ( $M_{200} \sim 10^{10} M_\odot$ ) most of the baryons are in the form of gas, while in the highest mass haloes we study ( $M_{200} \sim 10^{12} M_\odot$ ) a substantial amounts of gas forms stars.

Christensen et al. (2016) run twenty galaxy simulations spanning the mass range from  $10^{9.5} - 10^{12} M_\odot$  using zoom-in cosmological hydrodynamic simulation code and didn't only reproduce the stellar mass



**Figure 1.** Fractional baryon content of our NIHAO simulations as a function of halo mass. The green points show the ratio between the baryonic mass (stars + gas) inside the virial radius and the total baryonic mass associated with the dark matter halo. The blue points show the corresponding fraction for the stars. The solid green line and shaded region shows a double power-law fit, together with the  $1\sigma$  scatter. For the stellar mass fraction we show several relations from halo abundance matching. The linear (upper panel) and logarithmic (lower panel) scales emphasize the large amount of “missing” baryons, and the power-law nature of the relations, respectively.

- halo mass relation but also showed a similar baryon fraction relation, e.g. in  $L^*$  galaxies, the fraction is reduced by 20% while in galaxies with halo mass  $< 10^{10} M_\odot$  there can be as large as an 80% mass reduction. This suggests that the potential well of the halo regulates the baryon fraction. Meanwhile, van de Voort et al. (2016) have similar result produced by zoom-in cosmological hydrodynamic simulation suit FIRE which has 16 galaxies with similar halo mass range. Fig. 2 compares baryon and stellar fraction with van de Voort et al. (2016) and ?, we derive new baryonic mass and stellar mass within  $R_{500}$  and  $R_{100}$  to make sure the ratios compared in each panel have same definitions with ratios from other simulation suites. The baryon fraction in NIHAO simulations have good agreement with both of the simu-

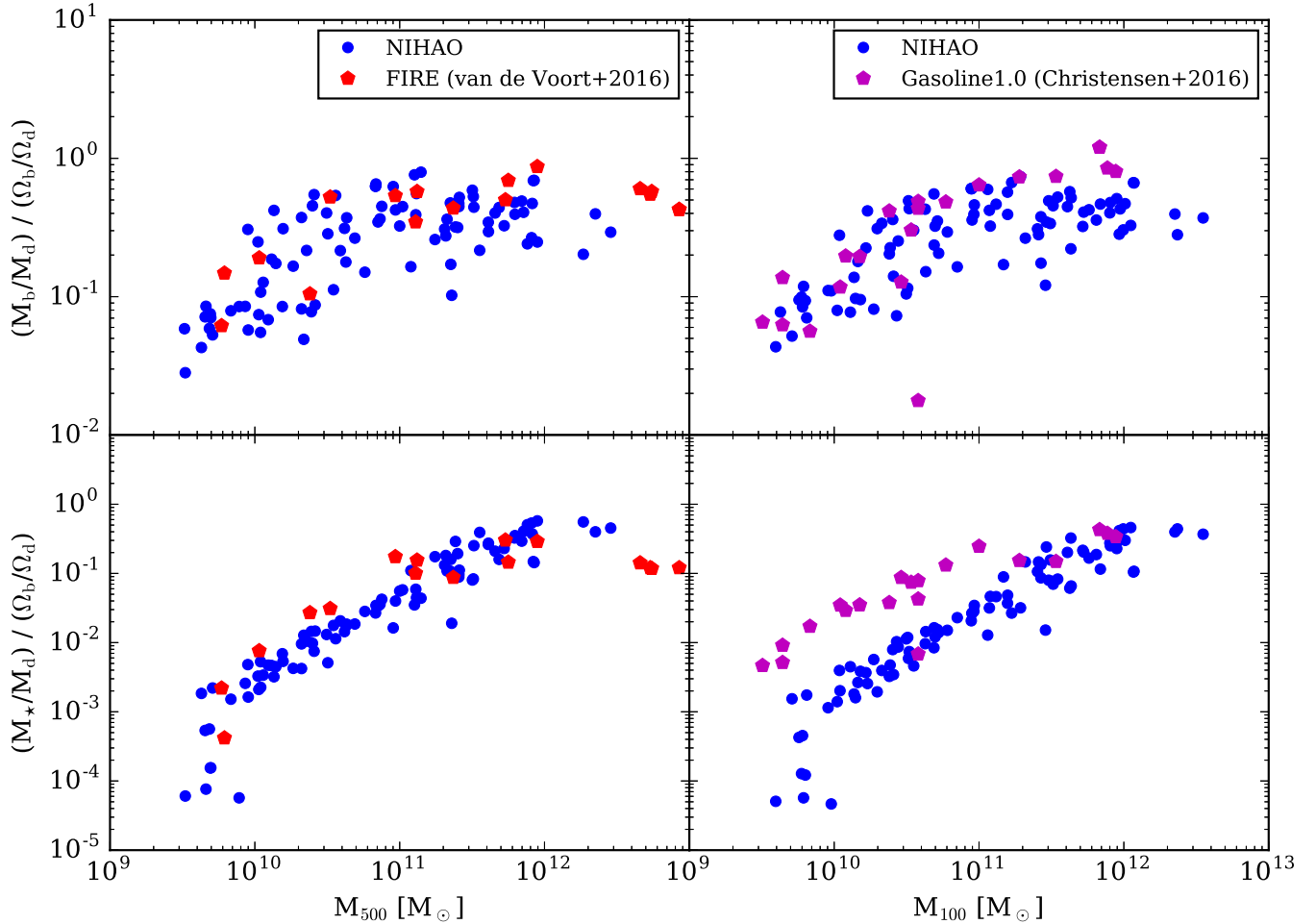


Figure 2. Upper panel shows baryon fraction comparing with van de Voort et al. (2016) (left) and Christensen et al. (2016) (right), and lower panel shows stellar fraction comparing with van de Voort et al. (2016) (left) and Christensen et al. (2016) (right). The blue points are from this work, the red pentagons are from van de Voort et al. (2016) and the magenta pentagons are from Christensen et al. (2016).

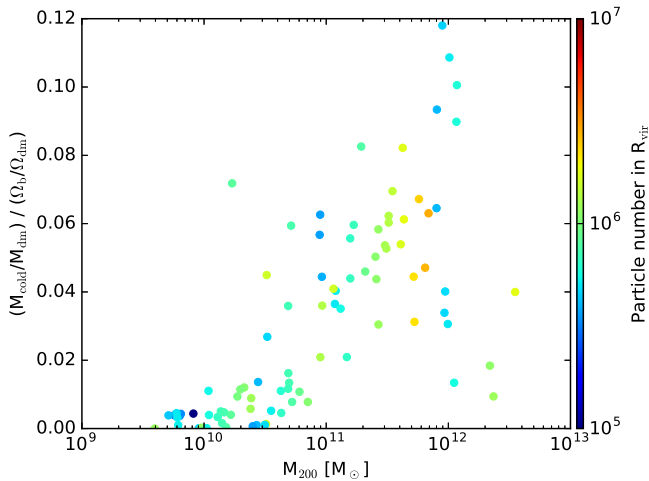


Figure 3. Linear fractional baryon content of our NIHAO simulations as a function of halo mass color coded by number of all particles per halo.

lation suite in the whole mass range where NIHAO simulations explored. For the massive haloes with  $M_{500} > 10^{12} M_{\odot}$ , there are two galaxies from NIHAO have reduced baryon fraction and four more massive galaxies from FIRE have larger reduced baryon fraction which may hint that the baryon fraction will decrease as the halo mass increases in large mass range. For stellar fraction, van de Voort et al. (2016) shows a almost same result with our work, even at low mass range, the two galaxies may suggest the large scatter as we produced.

Since most of the haloes we study are above the mass where the cosmic UV background prevents gas from cooling, the missing baryons have most likely been ejected from the central galaxies in supernova/stellar feedback driven winds. Although the lower mass galaxies have converted a smaller fraction of their available baryons into stars, and hence there is proportionally less energy available to drive an outflow, they have expelled a larger fraction of their baryons, consistent with expectations from energy driven gas outflows (e.g., Dutton 2012).

The behavior of the baryonic mass fraction,  $f_{\text{bar}}$ , as a

function of the halo mass is captured using a double power law formula:

$$\frac{f}{f_0} = \left( \frac{M_{200}}{\mathcal{M}_0} \right)^\alpha \left\{ 0.5 \left[ 1 + \left( \frac{M_{200}}{\mathcal{M}_0} \right)^\gamma \right] \right\}^{\frac{\beta-\alpha}{\gamma}}. \quad (2)$$

In this formula, the lower and higher mass ends have logarithmic slope  $\alpha$  and  $\beta$ , respectively, while  $\gamma$  regulates how sharp the transition is from the lower to the higher ends. The best fit parameters are as follows:

$$\begin{aligned} \mathcal{M}_0 &= 6.76 \times 10^{10} \\ f_0 &= 0.336 \\ \alpha &= 0.684 \\ \beta &= 0.205 \\ \gamma &= 3.40 \end{aligned} \quad (3)$$

The green shaded region indicates the scatter about the best fit line, which is 0.151 dex for haloes with mass in the range of  $3 \times 10^9 M_\odot < M_{200} < 2 \times 10^{10} M_\odot$ , 0.236 for halo mass in  $2 \times 10^{10} M_\odot < M_{200} < 7 \times 10^{10} M_\odot$ , 0.125 for halo mass in  $7 \times 10^{10} M_\odot < M_{200} < 3 \times 10^{11} M_\odot$  and 0.0518 for halo mass in  $3 \times 10^{11} M_\odot < M_{200} < 3.5 \times 10^{12} M_\odot$ .

As might be expected, haloes with the highest masses we study have high baryon fractions with relatively small scatter. As halo mass decreases, the baryon fraction decreases and the scatter increases, consistent with expectations from outflows driven by stellar feedback **since the energy-driven wind model determined that mass loading factors show a power-law dependency on circular velocity, with an exponent of  $\approx -2$ , e.g. Christensen et al. (2016), which means the greater efficiency of small galaxies at driving outflows is simply a result of their shallower potential well and the increasing scatters come from the increasing scatters of stellar mass halo mass relation in lower mass range.** At the lowest halo masses we study, below  $10^{10} M_\odot$ , the scatter starts to decrease. By contrast the scatter in the stellar mass fraction increases below this scale. Thus it seems unlikely that stellar feedback is primarily responsible for the low baryon fractions. Rather, we suggest an increased importance of the UV background, which heats gas to above the virial temperature, thus preventing it from collapsing into the low mass haloes. **Although the three most massive galaxies in NIHAO suite have fairly high stellar masses (see blue filled circles in Fig. 1), they don't have large deviations apart from the fitting baryon fraction, and in the comparison with FIRE (see Fig. 2), these three objects seem to hint the trend on massive galaxy end associated with the data from van de Voort et al. (2016). Moreover, the fitting relation about the baryon fraction is not sensitive to these three most massive galaxies as well since they have equal weight with other more than 80 galaxies to shape the fitting curve.**

Since the resolution is one key parameter in simulation, and one can imagine that with increased resolution, higher densities can be achieved in the CGM, potential leading to more cooling and larger cold/cool gas fraction, the convergence of the baryonic fraction predicted by NIHAO suite is worth to estimate. Fig. 3 shows cold and cool gas (HI + HeI) fraction color coded by number of dark matter parti-

cles per halo. In the plot, the number of dark matter particles per halo spans 2 magnitudes and has no correlation with cold and cool gas fraction. Therefore, we can conclude the resolution of NIHAO suite is proper to study the fractional baryon content.

### 3.1 Mass budget of the corona

In Fig. 4, we present the radial distribution of gas in different phases at  $z = 0$ , normalized to the total baryonic mass profile, such that, in the region far away from central galaxy where the stars are rare, for a given halo the four phases add up to unity, **each line is colour coded to the virial mass.** All simulations share a common attribute. The cold gas ( $T < 10^4$  K) is mostly located near the center ( $R < 0.2R_{200}$ ) where most stars in galaxies form. In contrast, the cool ( $10^4 \text{K} < T < 10^5 \text{K}$ ) and warm-hot ( $10^5 \text{K} < T < 10^7 \text{K}$ ) gas are located at large distances with roughly constant fractions up to 2 times  $R_{200}$ . The hot gas ( $T > 10^7 \text{K}$ ) is a minority component for all galaxies in the NIHAO sample, with the maximum hot gas fraction at any radius being less than 5%.

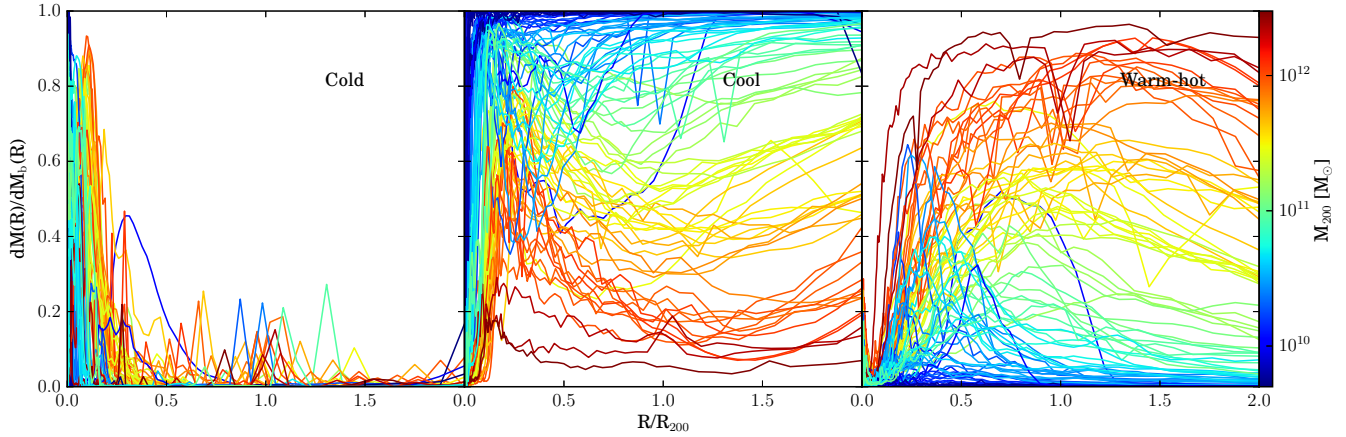
Despite these similarities, we find a considerably higher proportion of cool gas in lower mass galaxies ( $M_{200} < 10^{11} M_\odot$ ) in the whole corona region. For higher mass galaxies, warm-hot gas dominates the corona which signals **stronger virial shock** and higher efficiency of feedback. Even beyond the virial radius, the cool and warm-hot gas has similar features as the gas within virial radius which reveals the gas surrounding galaxies within large distance is the major reservoir of baryons.

### 3.2 Where are the missing baryons?

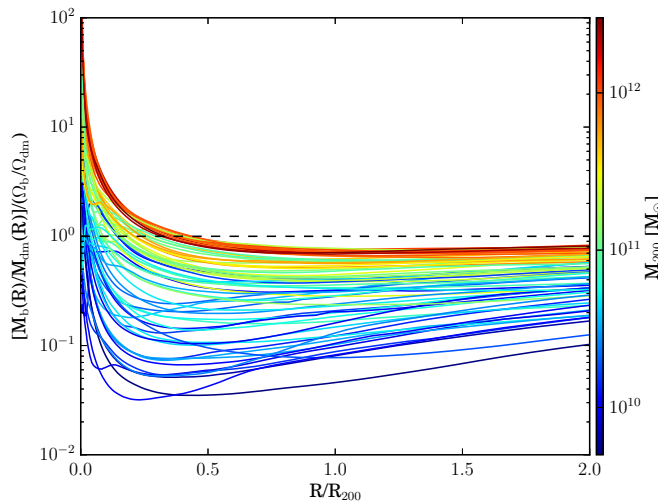
Fig. 5 shows the **cumulative fraction** of total baryons for each simulation. Here the y-axis is the ratio between the baryonic to dark matter mass,  $M_b(< R)/M_{\text{dm}}(< R)$ , enclosed within a sphere of radius,  $R$ , normalized by the cosmic baryon-to-dark matter ratio,  $\Omega_b/\Omega_{\text{dm}}$ .

Each solid curve represents a halo, and the curves are coloured by their halo mass (red for high masses to blue for low masses). Broadly speaking, the curves have a similar shape, with a normalization that depends on halo mass. They have a cusp in the central region where the stars and cold gas dominate, then become flat in the outer region. More massive haloes have higher baryon fractions at all radii. At small radii, the baryon to dark matter ratio is higher than the cosmic value due to gas dissipation. Even beyond the virial radius, there is little change in the baryon fraction up to 2 virial radii. We thus conclude that the missing baryons are well outside of the virial radius.

Two cosmological hydrodynamic simulations in Ford et al. (2015) which employed two prescriptions for galactic outflow models to compare with COS-Halos showed this cumulative baryon fraction profile for COS-Halos matched sample of galaxies. One hybrid energy/momentum driven winds model ("ezw" model) makes up to 65% of all baryons inside the halo. This is broadly consistent with estimates of baryonic mass derived from Werk et al. (2014) and our finding in Fig. 1. Comparing the cumulative



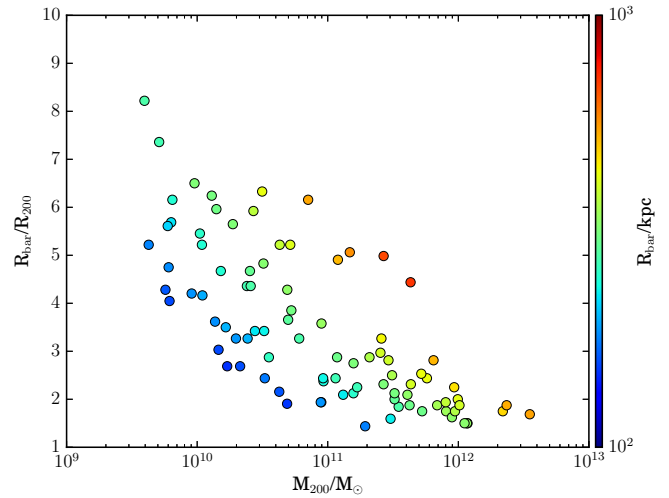
**Figure 4.** Radial profile of the mass fraction of the gas in each phase to total baryonic mass in each radial bin at  $z = 0$  for all galaxies in NIHAO sample. Each solid line is from one galaxy and colour coded with the halo mass.



**Figure 5.** Baryon distribution of each galaxy from NIHAO simulations. The lines are colour coded by their halo mass, which shows a clear trend that the more massive haloes preserve more baryons at all radii.

baryon fraction profile in detail, Fig.10 in Ford et al. (2015) shows the baryon fraction within  $0.1R_{\text{vir}}$  is only  $\sim 30\%$  and the fraction gradually increases to  $65\%$  at  $R_{\text{vir}}$  while the profile of galaxies with halo mass below  $10^{11}M_{\odot}$  in Fig. 5 have similar feature, the more massive galaxies all have roughly flat slopes. The simplified outflow model (constant wind model or “cw” model) shows lower fraction at all radii inside  $R_{\text{vir}}$  even though “ezw” model and “cw” model generally gives similar observational absorption line properties. This suggests that the profile of cumulative baryon fraction, as a complementary of total amount observation of CGM, is important to distinguish between competing outflow models that often closely relate to the feedback models.

To estimate how far the baryons escape, we measured the radius,  $R_{\text{bar}}$ , within which the total baryon mass equals to the fiducial baryonic mass defined by Eq. 1. This is a lower limit to the true extent of the missing baryons since

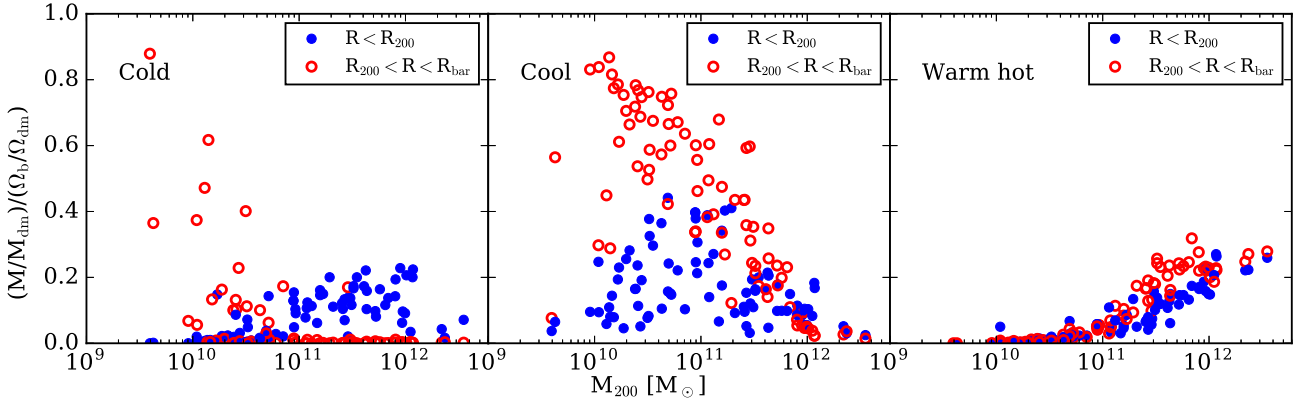


**Figure 6.** Normalized baryon radius as function of total virial mass. The points are colour coded by baryon radius of each galaxy.

the baryon mass includes gas and stars that belong to nearby lower mass haloes. Fig. 6 shows the baryon radius of each galaxy as function of the virial mass. We find the baryon radius generally increases with virial mass. **when normalized by the virial radius, the distance baryons are ejected span a similar range of radii  $R_{\text{bar}}/R_{200} \sim 2 - 6$  and gradually decrease as halo mass rise, even the majority of massive galaxies have  $R_{\text{bar}} \sim R_{\text{vir}}$ .**

In Fig. 7, we show the mass fractions of gas (in four phases) inside the virial radius (filled blue points) and between the virial and baryon radius (open red points). The fractions of cold gas,  $f_{\text{cold}}$ , are shown in the left panel. Inside the virial radius  $f_{\text{cold}}$  increases gradually from zero at a halo mass of  $10^{10}M_{\odot}$  to  $\sim 20\%$  at a halo mass of  $10^{12}M_{\odot}$ . The gas outside the virial radius has the opposite and much stronger trend:  $f_{\text{cold}} \sim 50\%$  in haloes of mass  $10^{10}M_{\odot}$  and decreases to zero by halo masses of  $10^{11}M_{\odot}$ . The fractions of cool gas,  $f_{\text{cool}}$ , are shown in the middle panel. Inside the virial radius,  $f_{\text{cool}}$ , has a maximum of  $40\%$  at a halo mass of  $10^{11}M_{\odot}$ , and declines to less than  $10\%$  below and





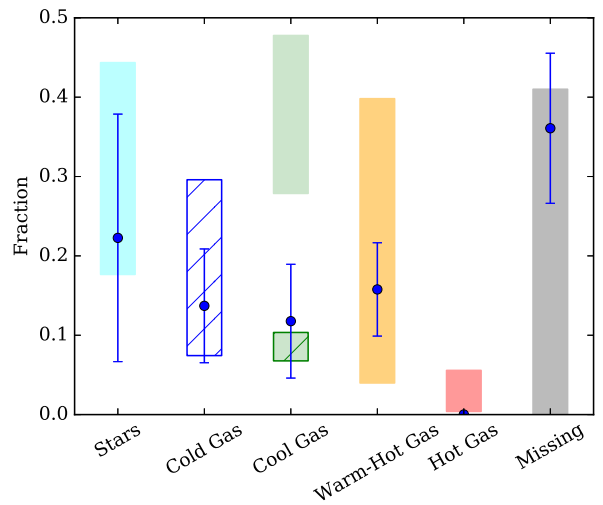
**Figure 7.** Mass fraction of gas in four phases (relative to the fiducial baryonic mass within the virial radius) **gas inside the virial radius** (filled blue points) and **between virial and baryon radius** (open red points), respectively. Cool gas is the dominant component of the fiducial baryonic mass within the virial radius for most galaxies ( $10^{10} < M/M_{\odot} < 10^{12}$ ), cold and warm-hot gas is majority only for the galaxies at lower and higher mass end.

above halo masses of  $10^{10}M_{\odot}$  and  $10^{12}M_{\odot}$ , respectively. For most haloes there is more cool gas outside than inside the virial radius. In haloes of mass  $10^{10}M_{\odot}$ ,  $f_{\text{cool}} \sim 80\%$ , and decreases to less than 10% by a halo mass of  $10^{12}M_{\odot}$ . The fractions for warm-hot gas,  $f_{\text{warm}}$ , are shown in the **right** panel. The trends of the gas inside and outside the virial radius are quite similar,  $f_{\text{warm}}$  increases monotonically with halo mass with maximum values of  $\sim 30\%$ . The hot gas **isn't shown** since it is negligible both inside and outside the virial radius across the whole mass range we study. We thus conclude that, for galaxies with halo masses in the range  $10^{10} \lesssim M_{200} \lesssim 10^{11}M_{\odot}$ , the majority of baryons associated with the dark matter halo are in the cold and cool phases, and are located well outside of virial radius. For haloes in the mass range  $10^{11} \lesssim M_{200} \lesssim 10^{12}M_{\odot}$ , the fractions of cold gas, cool gas and warm-hot gas are comparable.

### 3.3 Comparison with observations of Milky Way mass haloes

Observations can gain information of CGM from absorption lines and emission lines. Although emission lines allow us to directly obtain a 3D picture of the distribution of gas in the CGM, emission line studies preferentially probe the dense gas closer to galaxies since gas emissivity scales with the square of density. The situation is changing by building current facilities, e.g. Hayes et al. (2016), absorption line, however, is the most common observational constraints on the physical state of the CGM. The COSMOS survey is filling in details about the  $z \sim 0$  CGM (Peeples et al. 2014; Tumlinson et al. 2011, 2013; Werk et al. 2012, 2013, 2014). For the CGM of low-redshift  $\sim L^*$  galaxies ( $M_{\text{star}} \sim 10^{10.5}M_{\odot}$ ), Tumlinson et al. (2013) and Peeples et al. (2014) constrain the mass of the warm-hot CGM ( $T \sim 10^{5-7}K$ ), Werk et al. (2014) provides a strict lower limit to the mass of cool material ( $T \sim 10^{4-5}K$ ) in the CGM of these galaxies. In a study using X-rays, Anderson et al. (2013) place constraints on the mass of hot gas ( $T > 10^7K$ ) residing in the extended hot halos.

In Fig. 8, we show the mean values and standard deviation of the mass fraction of stars and different components



**Figure 8.** Baryonic budget of NIHAO haloes of mass  $3.5 \times 10^{11} < M_{200}/M_{\odot} < 3.5 \times 10^{12}$  (blue points with  $1\sigma$  error bars) compared with observations of  $M_{200} \sim 10^{12}M_{\odot}$  haloes (shaded regions). There is good agreement, except for the cool gas which has two conflicting measurements.

of gas in our most massive galaxies ( $3.49 \times 10^{11}M_{\odot} < M_{200} < 3.53 \times 10^{12}M_{\odot}$ ) with blue points and error bars. The gas is assigned to a range of temperature bins: cold gas ( $T < 10^4 K$ ), cool gas ( $10^4 K < T < 10^5 K$ ), warm gas ( $10^5 K < T < 10^7 K$ ) and hot gas ( $T > 10^7 K$ ). The observational constraints are shown with the same colour scheme in Fig. 11 in Werk et al. (2014).

In this plot Werk et al. (2014) provides observational constraints for CGM gas mass that are shown as the shaded bars. The stellar mass range comes from halo abundance matching as described in Kravtsov et al. (2014). The cold disk gas mass comes from Dutton et al. (2011).

The observations and the simulations match well in every phase except the cool CGM gas, where the observations find  $3\times$  the mass that simulations predict. If the observations are correct, the simulations have either ejected cool gas too far, or they have created a CGM with the wrong mix of gas temperatures. The total gas fractions ( $0.39$  in

**Table 1.** The baryonic budget parameters for NIHAO galaxies in different halo mass bins. We refer to gas in the temperature range  $T < 10^4$  K as cold;  $10^4$  K  $\leq T < 10^5$  K as cool;  $10^5$  K  $\leq T < 10^7$  K as warm; and  $T \geq 10^7$  K as hot.

|                                                |                       |                       |                       |                       |
|------------------------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| $\langle \log_{10}(M_{200}/M_{\odot}) \rangle$ | $9.992 \pm 0.223$     | $10.588 \pm 0.143$    | $11.267 \pm 0.209$    | $11.963 \pm 0.278$    |
| $\langle \log_{10}(M_b/M_{\odot}) \rangle$     | $9.243 \pm 0.215$     | $9.829 \pm 0.139$     | $10.493 \pm 0.206$    | $11.176 \pm 0.273$    |
| $\langle M_*/M_b \rangle$                      | $1.61 \times 10^{-3}$ | $9.57 \times 10^{-3}$ | $6.43 \times 10^{-2}$ | 0.240                 |
| $\sigma_*$                                     | $1.63 \times 10^{-3}$ | $4.24 \times 10^{-3}$ | $5.02 \times 10^{-2}$ | 0.156                 |
| $\langle M_{\text{cold}}/M_b \rangle$          | $1.37 \times 10^{-2}$ | $3.92 \times 10^{-2}$ | 0.124                 | 0.130                 |
| $\sigma_{\text{cold}}$                         | $8.24 \times 10^{-3}$ | $4.08 \times 10^{-2}$ | $3.58 \times 10^{-2}$ | $7.78 \times 10^{-2}$ |
| $\langle M_{\text{cool}}/M_b \rangle$          | 0.103                 | 0.192                 | 0.203                 | 0.109                 |
| $\sigma_{\text{cool}}$                         | $7.56 \times 10^{-2}$ | 0.135                 | 0.138                 | $6.37 \times 10^{-2}$ |
| $\langle M_{\text{warm}}/M_b \rangle$          | $7.92 \times 10^{-4}$ | $1.48 \times 10^{-2}$ | $5.83 \times 10^{-2}$ | 0.167                 |
| $\sigma_{\text{warm}}$                         | $1.25 \times 10^{-3}$ | $6.53 \times 10^{-3}$ | $3.19 \times 10^{-2}$ | $6.05 \times 10^{-2}$ |
| $\langle M_{\text{hot}}/M_b \rangle$           | 0.000                 | 0.000                 | 0.000                 | $1.82 \times 10^{-4}$ |
| $\sigma_{\text{hot}}$                          | 0.000                 | 0.000                 | 0.000                 | $2.33 \times 10^{-4}$ |
| $\langle M_{\text{missing}}/M_b \rangle$       | 0.880                 | 0.744                 | 0.548                 | 0.350                 |
| $\sigma_{\text{missing}}$                      | $5.65 \times 10^{-2}$ | 0.137                 | 0.110                 | $9.66 \times 10^{-2}$ |

COS-HALOs, 0.41 in NIHAO) suggest the latter option. However, Stern et al. (2016) developed a new method to constrain the physical conditions in the cool CGM from measurements of ionic column densities. This new method combines the information available from different sightlines during the photoionization modeling, and was applied to the COS-HALOs data, yielding a total cool CGM mass within the virial radius of  $1.3 \times 10^{10} M_{\odot}$  which is shown by the green hashed bar in Fig 1 and is in good agreement with our prediction. As the Fig. 4 and Fig. 7 show, the cool gas is the most important component **for most galaxies in NIHAO simulation** ( $10^{10} < M/M_{\odot} < 10^{12}$ ), **the cold and hot gas only dominate for galaxies at lower and higher mass end in NIHAO suite. A new estimation for the baryonic fractions from a set of eight Milky Way-sized zoom-in cosmological simulations (Colin et al. 2016) is generally consistent with our results. The fraction of cool gas from their simulation is even lower ( $f_{\text{cool}} = 0.034$ ) than ours and the result from Stern et al. (2016). On the other hand, Peebles et al. (2014) gave a conservative observational estimate about warm-hot gas and showed that the fraction of gas in this phase is only 5%, which is the lower limit of the estimates from Werk et al. (2014) and less than the average values from Colin et al. (2016) ( $f_{\text{warm-hot}} \approx 24\%$ ) and our finding ( $f_{\text{warm-hot}} \approx 17\%$ ). Therefore, the mix temperature of CGM have large uncertainty and the more accurate knowledge of the physical properties of CGM are necessary to better understand the role of the CGM in galaxy formation. As the CGM of lower mass galaxies will soon be observed, Table 1 lists information about CGM mass fractions of the different components of gas in haloes down to a halo mass of  $\sim 10^{10} M_{\odot}$ .**

#### 4 SUMMARY

We have used the NIHAO galaxy simulation suite (Wang et al. 2015) to study the statistical features of the baryonic budget and distribution spanning halo masses of  $\sim 10^{10}$  to  $\sim 10^{12} M_{\odot}$ . NIHAO is a large (currently 88) set of high resolution cosmological hydrodynamical galaxy formation simulations. As shown in previous papers the NIHAO galaxies reproduce several key observed scaling relations. We summarize our results as follows:

- All of the NIHAO haloes have a lower baryon to dark matter ratio, inside the virial radius, than the cosmic baryon fraction. **Higher fractions of baryons are lost as the virial mass decreases in the mass range of  $\lesssim 10^{12} M_{\odot}$ . The trend confirmed with Christensen et al. (2016) and van de Voort et al. (2016), and associated by van de Voort et al. (2016), the trend at higher mass range may suggest the baryon fraction is reduced larger as virial mass increase.**

- Lower mass haloes have lost a larger fraction of their baryons, even though they convert a lower fraction of the baryons into stars.

- Cold gas ( $T < 10^4$  K) is mostly restricted to be within 0.2 virial radii. The cool gas ( $10^4 < T < 10^5$  K) dominates the corona at low masses ( $M_{200} \lesssim 3 \times 10^{11} M_{\odot}$ ) while the warm-hot gas ( $10^5 < T < 10^7$  K) dominates at high masses ( $M_{200} \gtrsim 3 \times 10^{11} M_{\odot}$ ).

- All haloes have less baryons than baryon mass derived by cosmic baryonic fraction even beyond 2 virial radii. The total baryons derived by cosmic baryonic fraction within virial radius can expand more than  $8R_{\text{vir}}$  for low mass haloes but less than  $2R_{\text{vir}}$  for high mass haloes.

- Cool gas is a major component of the total baryons within  $R_{\text{bar}}$  **for galaxies at mass range between  $10^{10} M_{\odot}$  to  $10^{12} M_{\odot}$  cold and warm-hot gas dominates only for galaxies at lower and higher mass end. Most of baryons are outside of the virial radius.**

- For the highest mass haloes in our study  $\sim 10^{12} M_{\odot}$  our simulations are consistent with the observed fractions of stars, cold gas, warm and hot gas (Werk et al. 2014). Peebles et al. (2014) showed a conservative observational estimate for warm-hot gas which is lower limit of the result from Werk et al. (2014) and the warm-hot fraction from our study is well within the range of less conservative estimates.

- For the cool gas we predict  $f_{\text{cool}} = 0.11 \pm 0.06$  which is significantly lower than the observations from COS-HALOs ( $f_{\text{cool}} = 0.28 - 0.48$ ), but is in excellent agreement with the analysis of Stern et al. (2016). **As in Colin et al. (2016), the simulations suggest that the fraction of cool gas is approximately 10%.**



## ACKNOWLEDGMENTS

We thank the two anonymous referees whose suggestions greatly improve the paper. **We thank Freeke van de Voort for kindly sharing data of the FIRE simulation.** GASOLINE was written by Tom Quinn and James Wadsley. Without their contribution, this paper would have been impossible. The simulations were performed on the THEO cluster of the Max-Planck-Institut für Astronomie and the HYDRA cluster at the Rechenzentrum in Garching; and the Milky Way supercomputer, funded by the Deutsche Forschungsgemeinschaft (DFG) through Collaborative Research Center (SFB 881) "The Milky Way System" (subproject Z2), hosted and co-funded by the Jülich Supercomputing Center (JSC). We greatly appreciate the contributions of all these computing allocations. AAD, GSS and AVM acknowledge support through the Sonderforschungsbereich SFB 881 The Milky Way System (subproject A1) of the German Research Foundation (DFG). The analysis made use of the pynbody package (Pontzen et al. 2013). The authors acknowledge support from the MPG-CAS through the partnership programme between the MPIA group lead by AVM and the PMO group lead by XK. LW acknowledges support of the MPG-CAS student programme. XK acknowledge the support from 973 program (No. 2015CB857003, 2013CB834900), NSFC project No.11333008 and the "Strategic Priority Research Program the Emergence of Cosmological Structures" of the CAS(No.XD09010000).

## REFERENCES

- Anderson, M. E., Bregman, J. N., Dai, X. 2013, *ApJ*, 762, 106
- Agertz, O., Moore, B., Stadel, J. 2007, *MNRAS*, 380, 963
- Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, *ApJ*, 770, 57
- Bell, E. F., McIntosh, D. H., Katz, N., Weinberg, M. D., 2003, *ApJ*, 585, 117
- Bregman, J. N. 2007, *ARAA*, 45, 221
- Cen, R. Y., Ostriker, J. P. 1999, *ApJ*, 514, 1
- Christensen, C. R., Davé, R., Governato, F., et al. 2016, *ApJ*, 824, 57
- Colin, P., Avila-Reese, V., Roca-Fabrega, S., et al. 2016, *ApJ*, in press
- Davé, R. 2009, *ASPC*, 419, 347D
- Davé, R., Oppenheimer, B. D., Katz, N., et al. 2010, *MNRAS*, 408, 2051
- Dutton, A. A., Conroy, C., van den Bosch, F. C., et al. 2011, *MNRAS*, 416, 322
- Dutton, A. A. 2012, *MNRAS*, 424, 3123
- Dutton, A. A., & Macciò, A. V. 2014, *MNRAS*, 441, 3359
- Ford, A. B., Oppenheimer, B. D., Davè, R., et al. 2013, *MNRAS*, 432, 89
- Ford, A. B., Werk, J. W., Davè, R., et al. 2016, *MNRAS*, 459, 1745
- Fukugita, M., Hogan, C. J., Peebles, P. J. F. 1998, *ApJ*, 503, 518
- Gutcke, T. A., Stinson, G. S., Macciò, A. V., et al. 2016, *arXiv:1602.06956*
- Haider, M., Steinhauser, D., Vogelsberger, M., et al. 2016, *MNRAS*, 457, 3024
- Hayes, M., Melinder, J., Östlin, G., et al. 2016, *arXiv:1606.04536*
- He, P., Feng, L. L., Fang, L. Z. 2005, *ApJ*, 623, 601
- Hopkins, P. F., Kereš, D., Oñorbe, J., et al. 2014, *MNRAS*, 445, 581
- Hummels, C. B., Bryan, G. L., Smith, B. D., et al. 2013, *MNRAS*, 430, 1548
- Keller, B. W., Wadsley, J., Benincasa, S. M., & Couchman, H. M. P. 2014, *MNRAS*, 442, 3013
- Kravtsov, A., Vikhlinin, A., & Meshcheryakov, A. 2014, *arXiv:1401.7329*
- Marasco, A., Marinacci, F., Fraternali, F. 2013, *MNRAS*, 433, 1634
- McGaugh, S. S., Schombert, J. M., de Blok, W. J. G., Zargursky, M. J. 2010, *MNRAS*, 408, 14
- Moster, B. P., Naab, T., & White, S. D. M. 2013, *MNRAS*, 428, 3121
- Muratov, A. L., Kereš, D., Faucher-Giguère, C., et al. 2015, *MNRAS*, 454, 2691
- Oppenheimer, B. D., Crain, R. A., Schaye, J., et al. 2016, *arXiv:1603.05984*
- Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, *A&A*, 571, AA16
- Peebles, M. S., Werk, J. K., Tumlinson, J., et al. 2014, *ApJ*, 786, 54
- Persic, M., Salucci, P. 1992, *MNRAS*, 258, 14
- Pontzen, A., Roškar, R., Stinson, G., & Woods, R. 2013, *Astrophysics Source Code Library*, 1305.002
- Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, *MNRAS*, 446, 521
- Shen, S., Wadsley, J., & Stinson, G. 2010, *MNRAS*, 407, 1581
- Sharma, P., McCourt, M., Parrish, I. J., Quataert, E. 2012, *MNRAS*, 427, 1219
- Shull, J. M., Smith, B. D., Danforth, C. W. 2012, *ApJ*, 759, 23
- Shull, J. M. 2014, *ApJ*, 784, 142
- Sokolowska, A., Mayer, L., Babul, A., Madau, P., Shen, S. 2016, *ApJ*, 819, 21
- Stern, J., Hennawi, J. F., Prochaska, J. X., Werk, J. K. 2016, *arXiv:1604.02168*
- Stinson, G. S., Seth, A., Katz, N., et al. 2006, *MNRAS*, 373, 1074
- Stinson, G. S., Brook, C., Prochaska, J. X., et al. 2012, *MNRAS*, 425, 129
- Stinson, G. S., Brook, C., Macciò, A. V., et al. 2013, *MNRAS*, 428, 129
- Stinson, G. S., Dutton, A. A., Wang, L., et al. 2015, *MNRAS*, 454, 1105
- Suresh, J., Rubin, K. H. R., Kannan, R., et al. 2015, *arXiv:1511.00687*
- Thom, C., Tumlinson, J., Werk, J. K. 2012, *ApJL*, 758, L41
- Tumlinson, J., Thom, C., Werk, J., et al. 2011, *Science*, 334, 948
- Tumlinson, J., Thom, C., Werk, J., et al. 2013, *ApJ*, 777, 59
- van de Voort, F., Schaye, J. 2012, *MNRAS*, 423, 2991
- van de Voort, F., Quataert, E., Hopkins, P. F., et al. 2016, *arXiv:1604.01397*
- Vogelsberger, M., Genel, S., Springel, V., et al. 2014, *MNRAS*, 444, 1518
- Wadsley, J. W., Stadel, J., & Quinn, T. 2004, *NewA*, 9, 137

- Wadsley, J. W., Veeravalli, G., & Couchman, H. M. P. 2008, MNRAS, 387, 427
- Wang, L., Dutton, A. A., Stinson, G. S., et al. 2015, MNRAS, 454, 83
- Weinmann, S. M., Pasquali, A., Oppenheimer, B. D., et al. 2012, MNRAS, 426, 2797
- Werk, J. k., Prochaska, J. X., Thom, C., et al. 2012, ApJS, 198, 3
- Werk, J. k., Prochaska, J. X., Thom, C., et al. 2013, ApJS, 204, 17
- Werk, J. k., Prochaska, J. X., Thom, C., et al. 2014, ApJ, 792, 8
- Yoshida, N., Furlanetto, S. R., Hernquist, L. 2005, ApJ, 618L, 91
- Zhu, W., Feng, L. L., Fang, L. Z. 2011, MNRAS, 415, 1093