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Star formation and multi-phase interstellar medium in the first galaxies

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Abstract. Star formation and metal enrichment in the first galaxies is discussed emphasizing similarities to the properties of dwarf spheroidal galaxies in the Local Universe. I present preliminary results from new radiation-hydrodynamic cosmological simulations for the formation of the first galaxies performed with the ART code. The simulations include a detailed model for star formation in a multi-phase ISM, including H_2 formation catalyzed by H^- and on dust grains. The first metals are provided by Population III stars, while Population II star formation takes place in resolved molecular clouds. The properties of the first galaxies in these new simulations are in agreement with previous lower resolution simulations in which was found remarkable similarities between the fossils of the first galaxies and the faintest dwarf spheroidal galaxies in the Local Group.

Key words. Dark ages, reionization, first stars – Stars: Population III – Cosmology: theory – ISM: general – Local Group – Galaxies:dwarf

1. Introduction

In cold dark matter cosmologies, small mass halos outnumber larger mass halos at any redshift. However, the lower bound for the mass of a galaxy is unknown, as are the typical luminosity of the smallest galaxies and their numbers in the universe. If an early population of dwarf galaxies did form in significant number, their relics should be found today in the Local Group. These relics have been named "fossils of the first galaxies." This talk is a review that summarizes ongoing efforts to simulate and identify these fossils around the Milky Way and Andromeda.

Simulating the formation of the first galaxies in a cosmologically representative volume is complex because the results are sensitive to feedback effects acting on cosmological scales and the uncertain initial mass function (IMF) of the first stars. Progresses can be made only if we can constrain our models with observations. HST has detected a few redshift $z = 10$ candidates, but the bulk of the first population of dwarf galaxies is still undetected. Even with JWST we may not be able to probe the bulk of this population if, as simulations seem

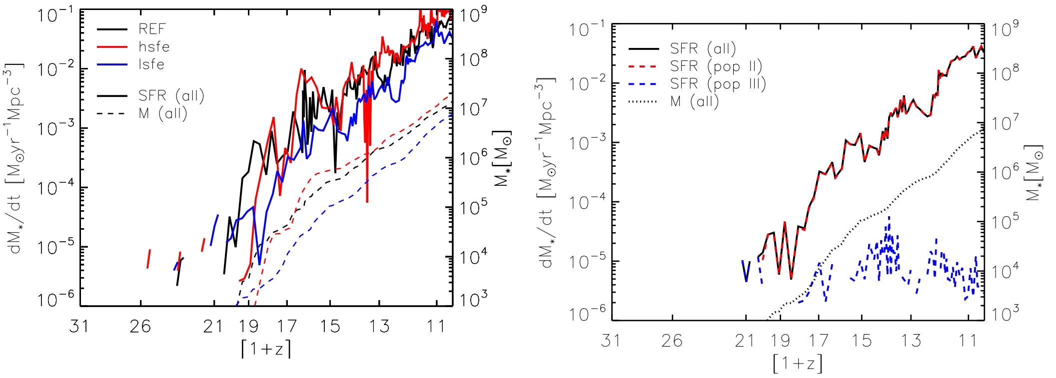

Fig. 1. (*(Left.)* Global star formation rate (SFR) (solid lines) and mass in stars (dashed lines) as a function of redshift in three simulations in which the sub-grid parameter that determines the star formation efficiency in molecular clouds was varied by a factor of 10 above and below a fiducial value. The SFR is self-regulated on a global scale. *(Right.)* Global SFR of population II stars (red solid line), population III stars (blue dashed line) and mass in stars (dotted black line) as a function of redshift.

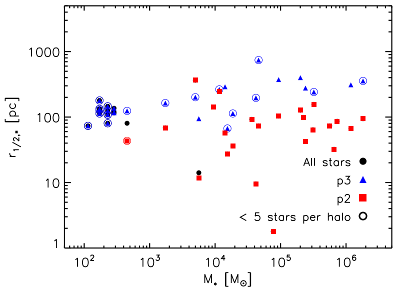

Fig. 2. Half-light radii as a function of luminosity of the stellar spheroids of the first galaxies at $z = 10$ in the simulations by Parry et al. (2014), in preparation. The triangles refer to the radial extent of Pop III stars only and the squares to Pop II stars only. The result agrees with previous lower-resolution simulations (Ricotti et al. 2002a; Ricotti & Gnedin 2005).

to suggest, is intrinsically faint. However, a promising avenue to constrain models of the first galaxies consists in using near field observations of the faintest dwarfs in the Local Group to identify the surviving fossils of the first galaxies (Ricotti & Gnedin 2005). The discovery of a population of ultra-faint dwarfs satellites of the Milky Way (Zucker et al. 2006; Belokurov et al. 2007; Majewski et al. 2007) with properties consistent with predictions of simulations of the fossils of the first galaxies (Bovill & Ricotti 2009; Salvadori & Ferrara 2009; Ricotti 2009, 2010), is an exciting observational development warranting further studies.

In this presentation I briefly review the timeline of progresses in this field (§ 2.1), and the main qualitative results from simulations of the formation of the first galaxies at $z > 10$ (§ 2.2). I then touch on metal production and enrichment of the interstellar medium (ISM) and intergalactic medium (IGM) (§ 2.3) and discuss the evolution of fossil dwarfs from formation to redshift $z = 0$ and the consistency of the models with observations of the Milky Way satellites (§ 2.4). I conclude with a brief summary (§ 3).

2. The first galaxies

In order to obtain sufficiently large densities to initiate star formation in dark matter halos, gas needs to cool by emitting radiation. In proto-galaxies with masses $> 10^8 - 10^9$ M$_\odot$, that typically form after the redshift of reionization ($z < 10$), the cooling is provided by hydrogen Lyman-alpha emission, that is efficient at temperatures $\sim 20,000$ K, but is negligible below $T \sim 10,000$ K. At temperature below $10,000$ K, typical of gas in the first small mass halos, cooling can only be provided by metal line cooling or by molecules. However, both these cooling mechanisms may be absent in the first galaxies. The first dwarf galaxies differ when compared to present-day galaxies in two main respects:

1. they lack important coolants – such as carbon and oxygen – because the gas initially is of primordial composition, and
2. due to the small typical masses of the first dark halos, the initial temperature of the gas is too low to cool by Lyman-alpha emission.

2.1. Timeline of progresses

A gas has primordial composition is unable to initiate star formation unless it can form a sufficient amount of primordial H_2 via the H^- chain. Tegmark et al. (1997) found that an abundance $x_{H_2} \gtrsim 10^{-4}$ is required to initiate the cooling and star formation. This requirement implies that the first luminous halos have masses $> 10^5$ $M_\odot$ and first appear at redshift $z \sim 30$.

Because molecular hydrogen is easily destroyed by far-ultraviolet (FUV) radiation in the Lyman-Werner bands ($11.3\ eV < h\nu < 13.6$ eV) emitted by the first stars, it was believed that the majority of galaxies with $v_{\rm vir} < 20$ km s^{-1} remain dark (*e.g.*, Haiman et al. 2000). However, several studies have now shown that even if the FUV radiation background is strong, a small amount of H_2 can form, particularly in relatively massive halos with virial temperature of several thousands of degrees (Wise & Abel 2007; O'Shea & Norman 2008). Thus, negative feedback from FUV radiation only delays star formation in the most massive dwarfs (Machacek et al. 2001, 2003). In a series of papers, Ricotti et al. (2002a,b, 2008) found that hydrogen ionizing radiation ($h\nu > 13.6$ eV) plays a far more important role in regulating the formation of the first galaxies than FUV radiation. Thus, models that do not include 3D radiative transfer of hydrogen and Helium ionizing radiation cannot capture the most relevant feedback mechanism that regulates galaxy formation in the early universe.

Around the epoch of reionization the formation of dwarf galaxies with mass $< 10^8 - 10^9$ $M_\odot$ (or circular velocity $v_{\rm vir} \lesssim 20$ km s^{-1}), is inhibited by the increase in the Jeans mass in the IGM. Thus, reionization feedback and negative feedback by the FUV background determine the mass of the smallest galactic building blocks. However, relatively recent episodes (at $z < 1$) of gas accretion and star formation may take place in some fossils of the first galaxies that evolve in isolation due to their large concentration (or equivalently, large mass for a given circular velocity) and the decreasing temperature of the intergalactic medium after Helium reionization at $z \lesssim 3$ (Ricotti et al. 2000). Fossil dwarfs may be characterized either by a single old population of stars or by a bimodal star formation history (Ricotti 2009).

2.2. Modern simulations

The first simulations of the the formation of the first galaxies in a cosmological volume including 3D radiation transfer were published

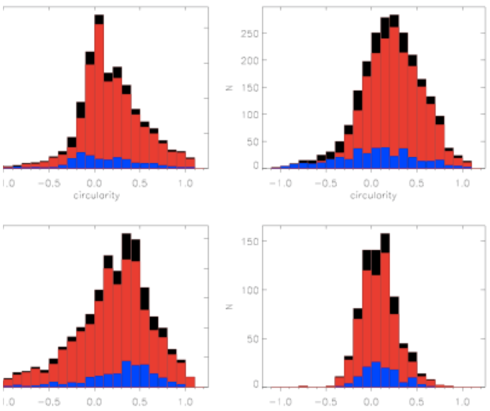

Fig. 3. Circularity of population II stars (red histograms) and population III stars (blue histograms) in four first galaxies at $z = 10$ in the simulations by Parry et al. (2014), in preparation. The circularity is defined as the angular momentum normalized to the angular momentum of a circular orbit with the same energy. The symmetry of the distribution around zero indicates that the stars in the first galaxies form as spheroids with little rotation.

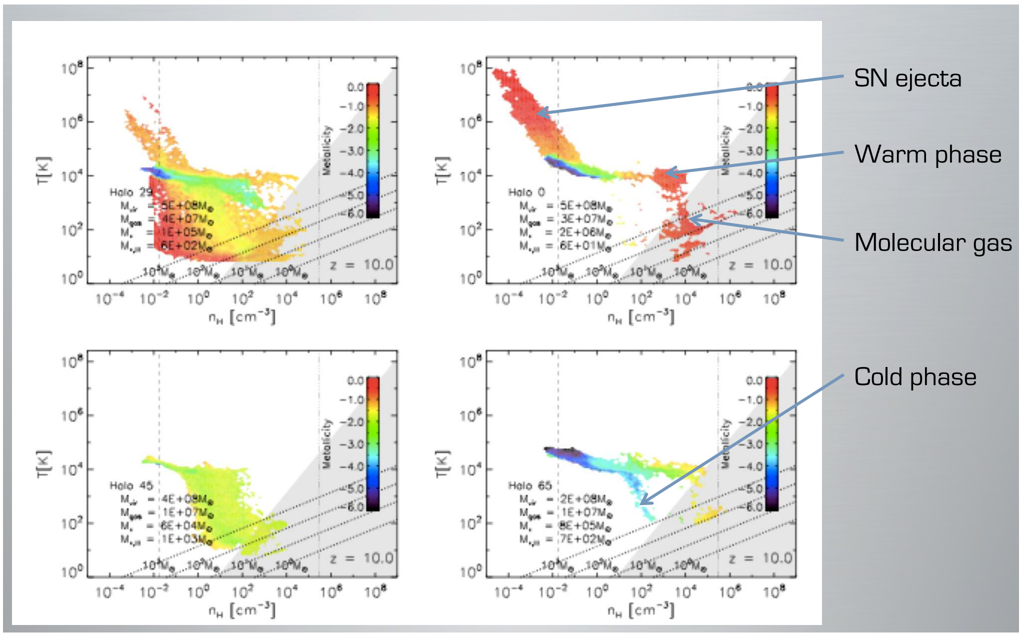

Fig. 4. Multi-phase ISM in four of the most massive galaxies at $z = 10$ in 1 Mpc^3 volume in the simulations by Parry et al. (2014), in preparation.

more than a decade ago (Ricotti et al. 2001, 2002a,b). Since then, many progresses have been made on understanding the formation of the first stars and Population II star formation in molecular clouds (*e.g.*, Wise et al. 2012; Muratov et al. 2013, Parry et al. 2014, in preparation)

Today's adaptive mesh refinement (AMR) simulations have sufficient resolution to resolve the multi-phase ISM and molecular clouds in dwarf galaxies. However, the main qualitative results found in early works have been confirmed by modern AMR simulations. Here is a concise summary of the main qualitative results:

1. Star formation on cosmological volume scales is self-regulated by feedback loops and is nearly independent of the star formation efficiency assumed in molecular clouds. This is illustrated in Figure 1(left).
2. Population III star formation becomes rapidly subdominant with respect to population II star formation unless the IMF of population III stars is such as to lead to direct collapse of black holes with little or no metal pollution (Ricotti & Ostriker 2004b,a)[see Figure 1(right)].
3. Near a mass threshold of $10^6 - 10^7$ $M_\odot$ a significant fraction of dark matter halos remain dark and the scatter of the M/L ratio at these masses is very large.
4. Primordial dwarf galaxies have stars distributed in spheroids (Figure 3) with half-light radii 100 – 500 pc nearly independently of their luminosity (see Figure 2).
5. Simulations find about 10-100 luminous dwarf galaxies per Mpc^3 at $z = 10$, but is not yet clear whether these simulations have converged. Population III star formation is still implemented using a subgrid recipe, but the gravitational potentials at the center of minihalos of mass $10^5 - 10^6$ $M_\odot$ are not resolved with a sufficient number of dark matter particles to allow the collapse of Population III stars that seed the subsequent Population II star formation.

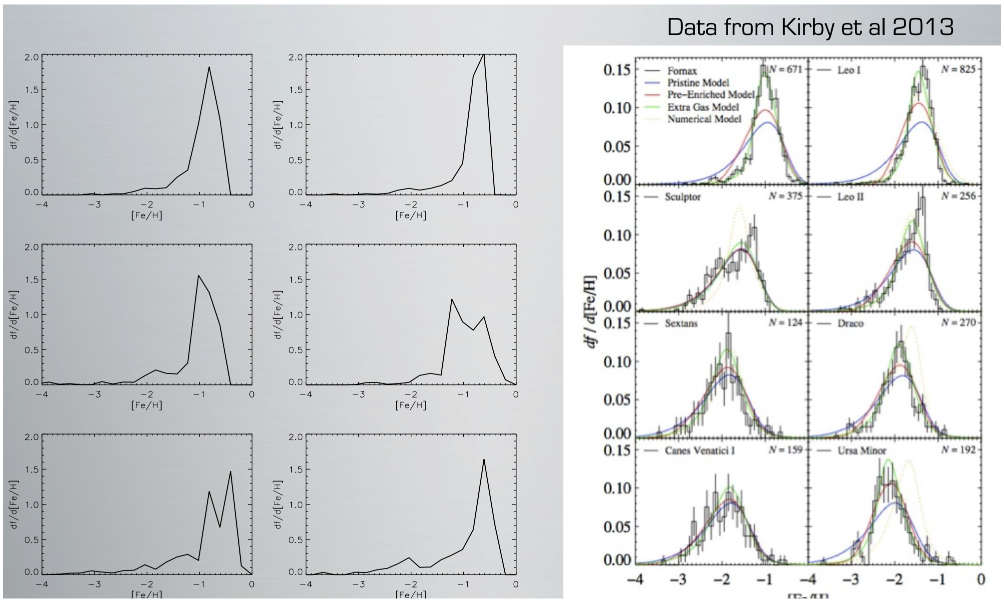

Fig. 5. *(Left.)* Metallicity distribution of stars in six of the most massive galaxies at $z = 10$ in 1 Mpc^3 volume in the simulations by Parry et al. (2014), in preparation. *(Right.)* Observations of the metallicity distribution of stars in eight local group dwarf galaxies from Kirby et al. (2011).

2.3. Metals and multi-phase ISM

The improvements in resolution of AMR simulations allow to model the physics of multiphase ISM and star formation in molecular clouds (see Figure 4). The treatment of star formation and Supernovae (SN) feedback in molecular clouds, although more realistic than in previous simulations adopting a Kennicutt-Schmidt law for star formation, is challenging for several reasons. All the processes important for the destruction and formation of molecular clouds need to be included and resolved in the simulations. Energy injection from SN explosions and radiation from massive stars is necessary to destroy molecular clouds. Since the scales of molecular clouds are barely resolved (the resolution is about 1 pc) simulations suffer the "overcooling" problem when the energy of SN explosions is injected in the dense molecular medium. Several approaches have been taken in the literature to avoid this problem: suppressing cooling, spreading the energy injection over neighboring cells, or including the effect of radiation pressure. In our simulations we do not include radiation pressure but we also do not take any other shortcut. The distribution functions of metallicity of stars are in good agreement with observations of local dwarfs (see Figure 5) but current simulations overproduce the mean metallicity of the stars for a given luminosity of the galaxy. The ineffectiveness of SN feedback in expelling metals from the ISM may also reduce the impact of the first galaxies on polluting the IGM with metals (see Figure 6).

2.4. Connection to near field cosmology

The recently discovered population of ultra-faint dwarfs (Zucker et al. 2006; Belokurov et al. 2007; Majewski et al. 2007) in combination with a proper treatment of observational incompleteness (Koposov et al. 2008) has increased the estimated number of Milky Way satellites to a level that can be more easily reconciled with theoretical expectations. For instance, the suppression of dwarf galaxy formation due to IGM reheating during reionization (Babul & Rees 1992; Hoeft et al. 2006;

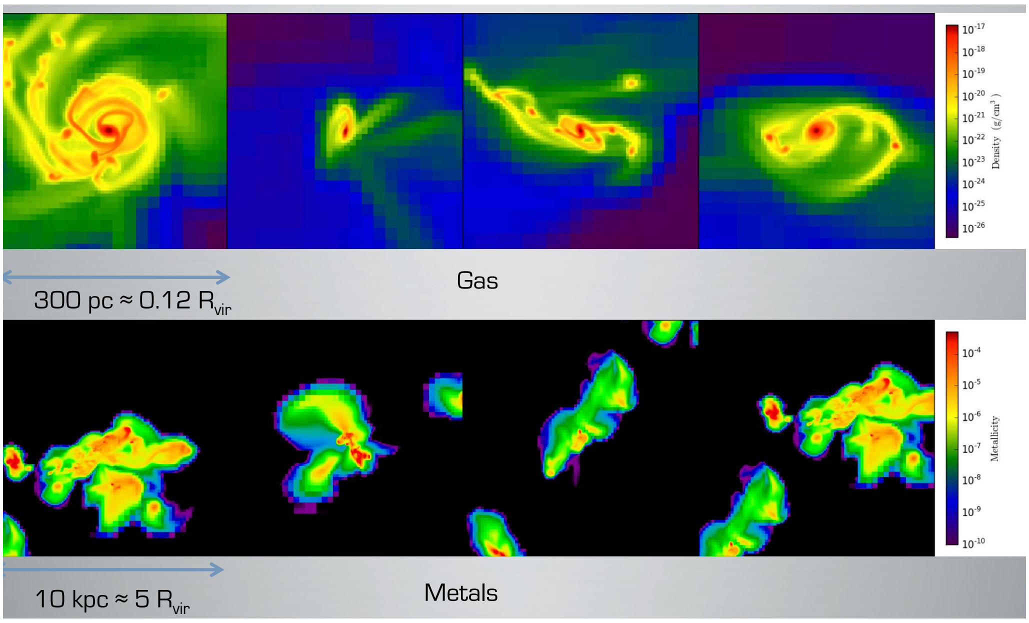

Fig. 6. Portrait of four of the most massive galaxies ($\sim 10^8$ $M_\odot$) at $z = 10$ in 1 Mpc^3 volume in the simulations by Parry et al. (2014), in preparation. The top panels show the gas density in a region of 300 pc and the bottom panels the gas metallicity in a region of 10 kpc around the same galaxies with color coding as indicated by the labels.

Okamoto et al. 2008; Ricotti 2009), in conjunction with a strong suppression of star formation in small mass pre-reionization dwarfs, is sufficient to explain the observed number of Milky Way satellites. We can now answer perhaps a more interesting question: what is the minimum mass that a galaxy can have? Answering this important question requires a good understanding of the feedback mechanisms that regulate the formation of the first galaxies before reionization, the details of the process of reionization feedback itself and understanding the properties of the dark matter on small scales (Polisensky & Ricotti 2011). Current observational data supports the thesis that a fraction of the new ultra-faint dwarfs recently discovered in the Local Group are in fact fossils of the first galaxies. Although destruction and tidal transformation of the Milky Way satellites and the identification of their masses at formation remain open questions, the age and metallicities of the stellar populations of several ultra-faints are consistent with their identification as fossils (Brown et al. 2012).

Theoretical modeling tells us that the population of first galaxies at $z = 10$ has different properties from the subset of surviving fossils at $z = 0$. In Bovill & Ricotti (2011a,b) we presented a method for generating initial conditions for LCDM N-body simulations which provide the dynamical range necessary to follow the evolution and distribution of the fossils of the first galaxies on Local Volume scales (5-10 Mpc) We show that he stellar properties of most of the ultra-faint dwarfs and classical dSph are consistent with those expected for the fossils and predict the existence of a yet undetected population of extremely low surface brightness dwarfs. Figure 7, taken from Bovill & Ricotti (2011a), shows a comparison of the properties of simulated fossils (shaded areas) and dwarfs galaxies in the Local Group. The asterisks are dIrr, crosses are dE, filled circles and triangles are the classical dSphs in the Milky Way and M31 respectively, and the opened circles and triangles are the ultra-faint populations. We color the observed dwarfs whose half-light radii are are inconsistent with our simulations in green. The magenta contours show the undetectable fossils with surface brightness below the detection limit (solid black lines) of the Sloan Digital Sky Survey (SDSS) (Koposov et al. 2008). In both panels, the dashed black lines show the trends from Kormendy & Freeman (2004) for luminous Sc-Im galaxies. A summary of the main properties of the fossils of the first galaxies at $z = 0$ is as follows:

1. Surviving fossils are anti-biased at $z = 10$ and tend to be underluminous for a given halo mass: most classical dwarfs leave in halos with $v_{max} > 20$ km/s, thus reionization does not have a strong effect on their star formation history.
2. The observed population of dwarfs with $r_h < 100$ has properties incompatible with simulated fossils. Their properties are most likely shaped by tides.
3. Models in which some of the ultra-faint dwarfs are fossils of the first galaxies agree well with observations of the ultra-faint dwarfs but show some tension at the bright end of the satellite luminosity function (classical dwarfs and dIrr). A numerous population of ultra-faint dwarfs also produces an overabundance of bright dwarf satellites especially in the outer parts of the Milky Way. However, this tension is eased by the expected large spatial extent of the old stellar population that forms a "ghost halo" difficult to detect and easily stripped by tides around bright satellites.
4. Indeed, the existence of diffuse stellar halos around isolated dwarfs is another observational test for the existence of the fossils of the first galaxies.

3. Summary and conclusions

Near field cosmology appears the most promising avenue to study the epoch of formation of the first stars and galaxies, also in light of the future surveys that will allow us to probe fainter and more distant ultra-faint dwarfs. From the theoretical point of view, the problem seems tractable but much progress needs to be made in our treatment of feedback processes. The effects of the first black holes and X-ray heating need to be better understood. In order to make a connection with detailed observations of stellar abundances in local dwarfs, the treatment of chemical enrichment needs to be improved by tracing the production of different elements, and their transport and mixing in the interstellar and intergalactic medium.

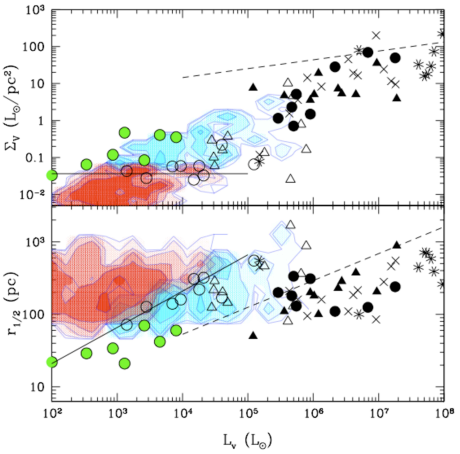

Fig. 7. Surface brightness and half light radius are plotted against V-band luminosity. The shaded contours show the distribution for the fossils in a simulation by Ricotti & Gnedin (2005) and the overlaid black symbols show the observed dwarfs. See the text for the explanation of symbols and lines.

From our studies to connect the fossils of the first galaxies to the satellites of the Milky Way, a good agreement is found between the fossils and the ultra-faints, however a problem persists at the bright end of the satellite luminosity function. The fossil light in the most massive satellites appears to exceed the observations with an excess of bright satellites especially in the outer parts of the Milky Way. This problem is alleviated if we hypothesize that the fossil stars are dynamically hot producing an extended "ghost stellar halo" with surface brightness below the detection limits or stripped by tides for satellites close to the Milky Way. It is thus conceivable that the mass-to-light ratio in small mass halos in not a monotonic function of the halo mass, and thus some of the classical dwarf satellites of the Milky Way may not reside in the most massive subhalos. This conjecture would also address a potential problem with the density of the most massive Milky Way satellites noted by Boylan-Kolchin et al. (2011). However, Polisensky & Ricotti (2013) showed that this problem is very sensitive to cosmological parameters, in particular to n_s and σ_8 that determine the power at small mass scales and thus the redshift of virialization and density of the Milky Way satellites. Adopting the most recent cosmological parameters and considering the uncertainty on the mass of the Milky Way, the problem is not severe, even assuming NFW profiles for the satellites.

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