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The living fossils of the first galaxies

M. Ricotti[1,2], O. Parry[1], E. Polisensky[1,3], and M. Bovill[4]

[1] University of Maryland, Department of Astronomy, College Park, 20742 MD, USA
e-mail: ricotti@astro.umd.edu
[2] Sorbonne Université, Institut Lagrange de Paris (ILP), 98 bis Bouldevard Arago 75014 Paris, France
[3] Naval Research Laboratory, Washington, D.C. 20375, USA
[4] Pontificia Universidad Católica de Chile, Avda. Libertador Bernardo O'Higgins 340, Santiago,Chile

Abstract. I will review ideas on the cosmological origin of dwarf galaxies in the Local Group focusing on the exciting possibility that some ultra-faint dwarfs are well preserved fossils of the first population of dwarf galaxies formed before reionization.

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

1. Introduction

In cold dark matter (CDM) cosmologies the number density of small mass halos per logarithmic mass bin is roughly inversely proportional to the halo mass. Is therefore important to determine what is mass of the smallest dark matter halos hosting luminous galaxies to answer questions on the number density of galaxies in the Local Group, the nature of the sources of ionizing radiation and metals in the early universe. Currently, the answer to these questions is uncertain and is the subject of ongoing research. Contrary to the formation of the first star in the universe, that is a relatively simple and well posed initial conditions problem, the formation of the first galaxies is complex because sensitive to feedback effects and the uncertain initial mass function (IMF) of the first stars.

As always, progresses can be made only if we can constrain our models with observations. HST has detected a few redshift ten 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 to suggest, is intrinsically faint. However, a promising avenue to constrain models of the first galaxies is emerging. It 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. Destruction and tidal transformation of the Milky Way satellites and the identification of the masses at formation of the ultra-

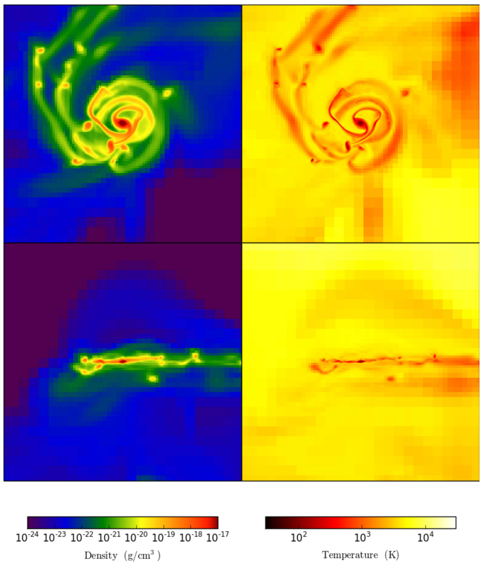

Fig. 1. Portrait of one of the most massive galaxies ($\sim 10^8$ M$_\odot$) at $z = 10$ in 1 Mpc^3 volume in the simulations by Parry et al. (2014), in preparation. The panels show the gas density and temperature as indicated by the labels.

faint dwarfs remain open questions, although the age and metallicities of the stellar populations of the ultra-faints is consistent with their identification as fossils (Brown et al. 2012).

In this presentation I will cover three related topics. First, I summarize the main qualitative results from simulations of the formation of the first galaxies at $z > 10$ (§ 2). I will then discuss issues related to their subsequent evolution to $z = 0$ and the consistency of the models with observations of the Milky Way satellites (§ 3). Finally I will focus on the most massive satellites of the Milky Way (§ 4) and conclude with a summary (§ 5).

2. New simulations of the first galaxies

The first simulations of the the formation of the first galaxies in a cosmological volume including 3D radiation transfer were published more than a decade ago (Ricotti et al. 2001, 2002a,b, 2008). 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 AMR simulations have sufficient resolution to resolve the multi-phase ISM and molecular clouds in dwarf galaxies (see Figure 1). However, the main qualitative results found in early works have been confirmed by modern adaptive mesh refinement (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 2.
2. Near a mass threshold of 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.
3. Primordial dwarf galaxies have stars distributed in spheroids with half-light radii 100 – 500 pc nearly independently of their luminosity (see Figure 3).
4. There are about 10-100 luminous dwarf galaxies per Mpc^3 at $z = 10$, but is not yet clear whether simulations have converged. Population III star formation is still implemented using a sub-grid recipe, but

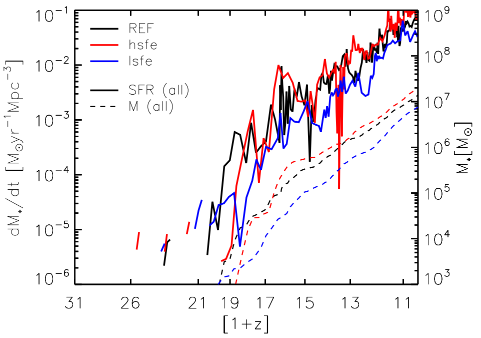

Fig. 2. Global star formation rate (SFR) (solid lines) and mass in stars (dashed lines) as a function of redshift in three simulations in which the sub-grid parameter that determines the star formation efficiency in molecular clouds was varied by a factor of 10 above and below a fiducial value. The SFR is self-regulated on a global scale.

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.

3. Connection to near field cosmology

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 which fall below the SDSS detection limit. Figure 4, 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 non-fossils (dIrr), crosses are polluted fossils (dE and some dSph), the 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 Σ_V below the detection limit of the SDSS (Koposov et al. 2008). In both panels, the solid black lines show the surface brightness limit of the Sloan and 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 (Ghost halos) is another observational test for the existence of the fossils of the first galaxies.

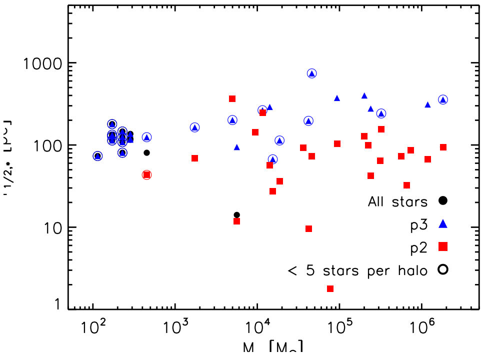

Fig. 3. Half-light radii as a function of luminosity of the stellar spheroids of the first galaxies at $z = 10$ in the simulations by Parry et al. (2014), in preparation. The triangles refer to the radial extent of Pop III stars only and the squares to Pop II stars only. The result agrees with previous lower-resolution simulations (Ricotti et al. 2002a; Ricotti & Gnedin 2005).

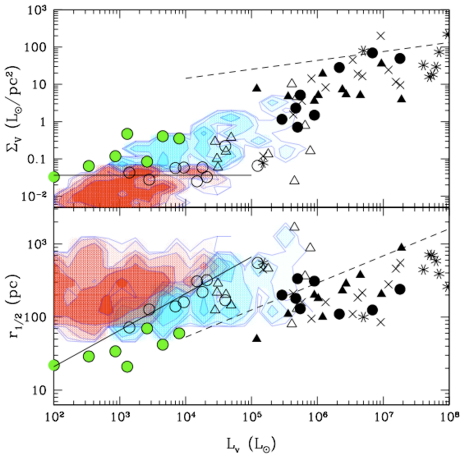

Fig. 4. Surface brightness and half light radius are plotted against V-band luminosity. The cyan contours show the distribution for the fossils in a simulation by Ricotti & Gnedin (2005) and the overlaid black symbols show the observed dwarfs. See the text for the explanation of symbols and lines.

4. Massive satellites of the Milky Way in cold and warm dark matter

Recent work focusing on the brightest Milky Way satellites has highlighted dynamical discrepancies with high-resolution CDM simulations (Boylan-Kolchin et al. 2011). The most massive satellites, either at the present epoch or over the complete infall history, are too dense to be dynamically consistent with the satellites. Observations of the stellar velocity dispersions in the bright satellites are consistent with dark matter halos with maximum circular velocities $<$ 25 km/s while the Aquarius Milky Ways have about 10 subhalos each with v_{max} $>$ 25 km/s that are also not Magellanic Cloud analogues.

We have re-examined this problem, known as the "too big to fail" (TBTF) problem in CDM and WDM cosmologies (Polisensky & Ricotti 2013). We find that the inconsistency is largely attributable to the large values of σ_8 and n_s adopted in the discrepant simulations (the Aquarius simulations has WMAP1 cosmology), producing satellites that form too early and therefore are too dense. Fig. 5 shows that the tension between observations and simulations adopting parameters consistent with WMAP9 is significantly diminished, making the satellites a sensitive test of CDM. Assuming NFW profiles for the satellites only a couple of dwarfs are still inconsistent with observations, suggesting that cored profiles are not required by current data.

Finally, adopting a power spectrum of perturbation with truncation at small mass scales, for instance produced by WDM, does not seem to solve the TBTF problem because the effect on the density of the satellites is significant only when the dark matter is sufficiently warm to suppress the number of satellites below the value allowed by observations (Polisensky & Ricotti 2011).

5. 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. We need to include the effects of the first black holes and X-ray heating, study in greater detailed chemical enrichment by tracing the production of different elements, and the transport and mixing of metals in the interstellar and intergalactic medium.

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

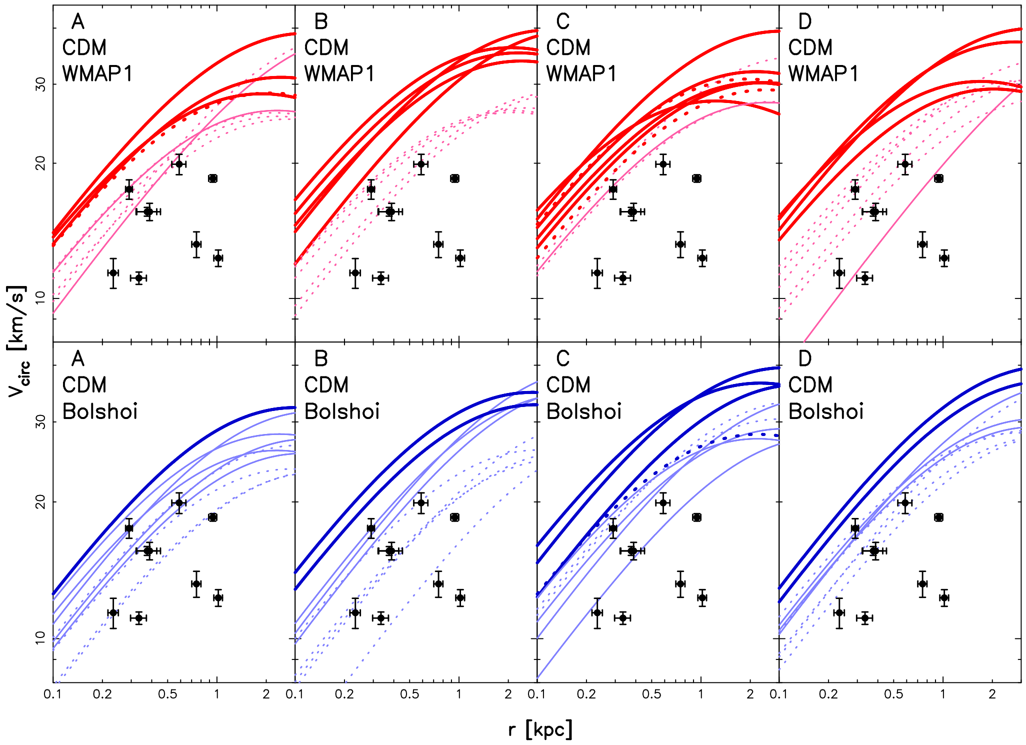

Fig. 5. NFW circular velocity profiles for the 10 subhalos with largest v_{max} at $z = 0$ in each CDM simulation adopting WMAP1 cosmology (top row); and Bolshoi cosmology (bottom row) after filtering Magellanic Cloud analogues. Subhalos denser than any observed dwarf (points with error bars) are plotted in bold. Subhalos that are neither among the 10 with largest v_{infall} or 10 largest v_{max} at $z = 9$ are not expected to host a bright dwarf and are plotted with dotted lines. Note that NFW profiles for the 10 subhalos with largest v_{max} over their infall history select a few subhalos with lower values of v_{max} and R_{max} than shown here, further alleviating the discrepancy with observations.

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 solve the TBTF problem noted by Boylan-Kolchin et al. (2011). However, Polisensky & Ricotti (2013) showed that the TBTF 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 the TBTF problem is not severe, even assuming NFW profiles for the satellites.

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