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Dwarf galaxies and the formation of the Milky Way

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Abstract

The formation of galaxies such as the Milky Way is still poorly understood. In our current cosmological paradigm, Cold Dark Matter (CDM), model predictions appear in tension with observations regarding (i) the existence of bulge-less galaxies and the relatively high angular momentum of spiral galaxies at a fixed mass (the so-called "angular momentum catastrophe"), (ii) the apparent overabundance of bound substructures expected in CDM halos (the "missing satellite problem"), and (iii) the absence of centrally-divergent density profiles (the so-called dark matter cusps) in the inner regions of galaxies (the "core/cup problem"). Baryonic feedback has been often invoked to solve CDM problems on small scales. However, while the formation of DM cores generally requires an efficient conversion of gas into stars, the suppression of star formation needed to reproduce the relatively small number of satellite galaxies observed in the Milky Way and M31 obviously requires the opposite. The effects of stellar evolution on dark matter halos appear as both a theoretical challenge and a promising solution to several problems faced by CDM.

1 Introduction

The Milky Way and her satellite galaxies are perhaps the best known galaxies in the Universe, and as such represent key systems to test predictions from the current cosmological paradigm (Cold Dark Matter, hereafter CDM).

The more precise and detailed the gathered data become, the more tensions appear to arise between theory and observations. Unfortunately, comparisons to cosmological models tend to be inconclusive for the simple reason that observations refer to baryonic material, whereas most CDM simulations only consider dark matter. Baryons introduce several complexities. First, the formation of stars and their impact on their surrounding medium still lack a theoretical understanding. Second, the dynamical interplay between stellar evolution and the distribution of DM in the inner-most regions of galaxies (also known as "stellar feedback") occurs on scales that lie beyond current computational capabilities. Furthermore, baryons also complicate the interpretation of observations within the CDM paradigm because any uncertainty (e.g., uncertain stellar mass-to-light ratios) in the baryonic mass profile propagates to the inferred dark matter profile, as the latter is merely the difference between dynamical and baryonic mass profiles.

Hydrodynamical CDM simulations seek a remedy to these limitations in what has been called *sub-grid physics algorithms*, which implement semi-analytical prescriptions for stellar processes that cannot be simulated self-consistently. Their goal is to reproduce in a phenomenological way what is observed in galaxies. The main problem faced by this approach is that, although these models provide a satisfactory description of observational data by tuning the parameters that describe involved baryonic processes, the apparent success does not necessarily validate the cosmological model that is being inspected.

In spite of the considerable theoretical freedom introduced by sub-grid physics, some fundamental properties of spiral galaxies are still in clear tension with CDM predictions. In particular, three problems challenge the CDM paradigm: (i) *the angular momentum catastrophe*, (ii) *the missing satellite problem* and (iii) *the core-cusp problem.*

[15] showed that spiral galaxies formed in cosmological simulations of structure formation rotate *too slowly* when compared with observations of external galaxies. Puzzlingly, their simple recipe for star formation, radiative cooling, UV background and feedback from evolving stars was able to reproduce the slope of the Tully-Fisher relationship, although it failed to provide a correct normalization. In particular, the specific angular momentum of stellar discs $\lambda_J \equiv |J|E^{1/2}/(GM^{5/2})$, where $|J|$ is the total angular momentum, $|E|$ is the gravitational energy and M the halo mass, predicted by these models at a specific galaxy mass was around one order of magnitude lower than observed. [11] have shown that bulge-less galaxies can be obtained in self-consistent hydrodynamical simulations by adopting new supernova feedback recipes. In these models strong outflows from supernovae remove low-angular-momentum gas in the accreted satellite galaxies, which inhibits the formation of bulges and decreases the dark-matter density to less than half of what it would otherwise be within the central kiloparsec of the spiral galaxy. Interestingly, violent supernova feedback also helps to increase the specific angular momentum of the galactic discs. The simulated galaxies form rotationally supported discs with realistic exponential scale-lengths and fall on both the I band and baryonic Tully-Fisher relations.

It appears therefore that the solution to the mismatch between observations of spiral galaxies and CDM expectations hinges on an even more thorny problem, that is the formation of stars from a gaseous medium and the effect of stellar evolution on the ISM.

Dwarf spheroidal galaxies (hereinafter dSphs) are supposed to sample the lowest-end of the galaxy mass spectrum, and as such provide key information on the effects of baryonic feedback on the surrounding DM distribution. Furthermore, all dSphs contain ancient stellar populations and are metal-poor, which constraints star formation models at high redshift [5]. dSphs are also among the most DM-dominated galaxies in the known Universe [9], which considerably simplifies the dynamical models that aim to unravel the distribution of DM on small scales.

This talk offers an overview of the latest investigations of dSphs within a cosmological context. It will be shown that observational data continue to disagree with the basic

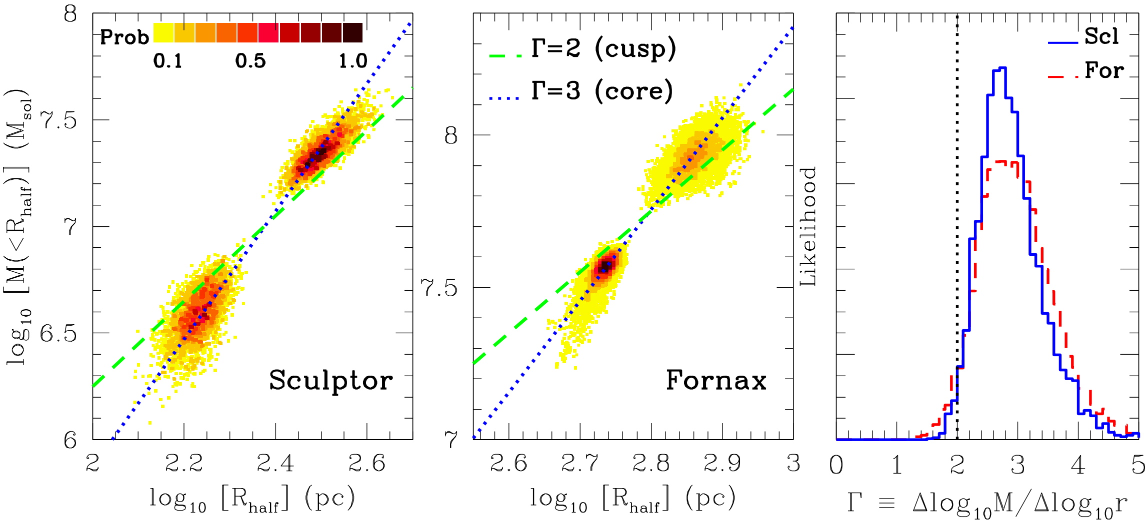

Figure 1: *Left and center panels:* Constraints on halflight radii and masses enclosed therein, for two independent stellar subcomponents in the Fornax and Sculptor dSphs. Plotted points come directly from our final MCMC chains, and color indicates probability density. Overplotted are straight lines indicating the central slopes of cored ($\lim_{r\to 0} d\log M/d\log r] = 3$) and cusped ($\lim_{r\to 0} d\log M/d\log r] = 2$) dark matter halos. *Right panel:* Posterior PDFs for the slope Γ obtained for Fornax and Sculptor. The vertical dotted line marks the maximum (i.e., central) value of an NFW profile (i.e., cusp with $\gamma_{\rm DM} = 1$, $\lim_{r\to 0}[d\log M/d\log r] = 2$). These measurements rule out NFW and/or steeper cusps ($\gamma_{\rm DM} \geq 1$) with significance $s \geq 96\%$ (Fornax) and $s \geq 99\%$ (Sculptor).

predictions from collision-less CDM simulations. It remains an open question whether or not the tensions between CDM expectations and observational data reflect a fundamental problem for our cosmological paradigm, or simply arise from our limited understanding of the formation and evolution of stars and their impact on the gaseous medium that surround them.

2 The distribution of DM in dwarfs

Recently, ([22]; WP11) used measurements of stellar positions, velocities, and spectral indices to identify distinct stellar components in the Fornax and Sculptor dSphs and measure the slope of the halo mass profile. The values, $\Gamma \equiv \Delta\log M/\Delta\log r = 2.61^{+0.43}_{-0.37}$ and $\Gamma = 2.95^{+0.51}_{-0.39}$ in Fornax and Sculptor (see Fig. 1), rule out NFW profiles ($\Gamma < 2$) at confidence levels $\sim 96\%$ and $\sim 99\%$. However, deriving the core size from measurements of Γ is hindered by the fact that, while the dynamical tracers lie, by definition, within the luminous radius, the DM core may reach far beyond the luminous confines of the galaxy.

If we adopt the following cosmologically-motivated halo density profile

$$\rho(r) = \frac{\rho_0 r_s^3}{(r_c + r)(r_s + r)^2}; \tag{1}$$

where ρ_0 is a characteristic halo density, r_s is a scale radius and r_c a core radius, the relation between the slope of the mass profile and the core size for stellar components that are deeply embedded within the DM halo (i.e. $r_{\rm h} \ll r_s$) is

$$\Gamma(r_{\rm h}) = 3 - \frac{3(1+2x)}{4x}\left(\frac{r_{\rm h}}{r_s}\right) + \mathcal{O}\left(\frac{r_{\rm h}}{r_s}\right)^2. \tag{2}$$

Two points can be gleaned from this Equation. First, measurements of $\Gamma(r_{\rm h})$ cannot be used to derive upper limits for the halo core radius, as the slope approaches an asymptotic value $\Gamma \simeq 3 - 3/2(r_{\rm h}/r_s)$ for $r_c \gg r_s$. And second, steep mass profiles ($\Gamma > 2.5$) imply that the dark matter core extends well beyond the luminous radius of the dwarf, i.e $r_c > r_{\rm h}$.

Fig. 2 illustrates the transformation defined by Eq. (1). We adopt a fiducial NFW model with $M_{\rm vir} = 3 \times 10^9 {\rm M}_\odot$, $r_s \simeq 1.9$ kpc and a concentration $c = 19.6$ (solid line), which is representative of the halos wherein MW dSphs are embedded (e.g. [21]). Long-dashed, dotted and short-dashed lines show cored profiles with $r_c = 0.2, 1.0$ and 5 kpc, respectively. The lower panel shows the slope of the mass profiles associated to these models. As expected from Eq. (2), the values of Γ measured in the Fornax (solid symbol) and Sculptor (open symbol) dSphs are suggestive of core sizes $r_c > 1$ kpc.

3 Baryonic feedback

The results outlined in the previous Section do not conform with the predictions from collision-less CDM simulations, which predict that galaxies must be embedded in dark matter halos that individually follow mass-density profiles characterized by centrally-divergent 'cusps', with $\rho(r) \propto r^{-1}$ at small radii ([3, 13] hereafter NFW). The dark matter halos inferred from observations of real galaxies differ significantly: the estimated mass profiles are consistent with homogeneous-density 'cores' (see [22] and references therein).

Indeed various baryon-physical mechanisms have been proposed and demonstrated to be capable of fixing this problem: e.g. supernova explosions [13, 20, 12, 19], or the orbital decay of compact baryonic objects [4, 10, 2] can under plausible conditions transform the central cusps of CDM-like halos into 'cores' of constant density.

Notice, however, that the solution to the core/cusp problem rests rest upon the efficiency with which stars form in DM halos. In particular, baryons must provide enough energy through feedback mechanisms in order to remove DM cusps. However, while core formation generally requires an efficient conversion of gas into stars, solutions to the small number of visible substructures found in the Milky Way and M31, i.e. the so-called "missing satellite problem" [6, 16], require a suppression of galaxy formation on the same mass scales.

In light of this apparent tension, [17] performed a simple calculation of the energy required to remove DM cusps on the mass scales of dSphs, and compared it with the kinetic

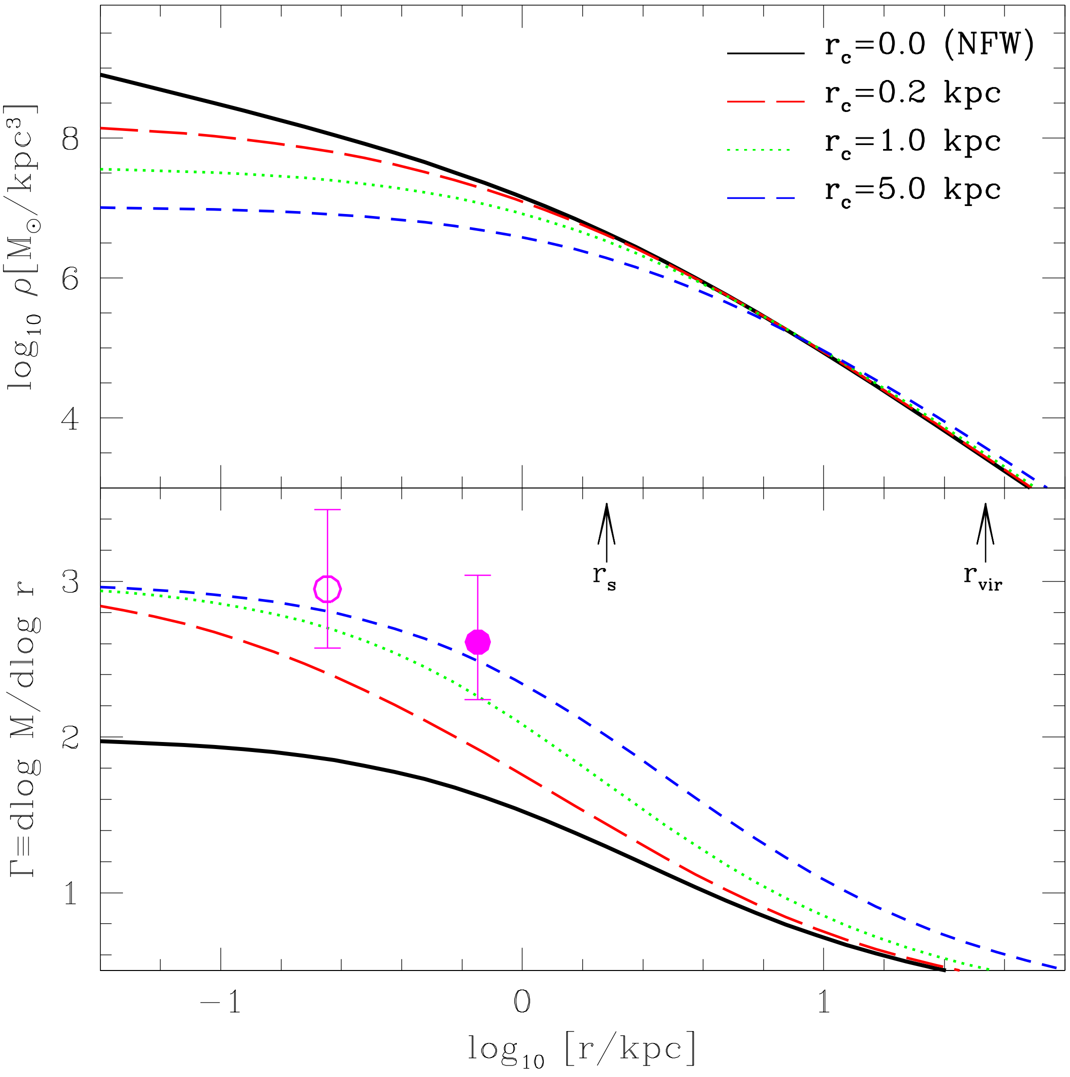

Figure 2: *Upper panel*: Density profiles considered in this work. Thick solid lines correspond to an NFW model with $M_{\rm vir} = 3\times10^9 {\rm M}_\odot$, scale radius $r_s \simeq 1.9$ kpc a concentration $c = 16$. Red, green and blue show cored density profiles of halos with the same virial mass and a core radius $r_c = 0.2, 1.0$ and 5 kpc, respectively. *Lower panel:* Slope of the mass profile $\Gamma = d\ln M/d\ln r$ as a function of radius for the above models. NFW and cored halos have $\Gamma < 2$ and $\Gamma < 3$, respectively. Recent measurements of Γ in the Fornax (closed symbol, $r_{\rm h} \simeq 713$ pc) and Sculptor (open symbol, $r_{\rm h} \simeq 226$ pc) dSphs are indicative relatively large ($r_c > 1$ kpc) DM cores in both galaxies (see WP11 for details).

energy generated by supernova type II (SNeII hereinafter) explosions. For a galaxy with a stellar mass $M_\star$, this can be estimated as

$$\Delta E \approx \frac{M_\star}{\langle m_\star \rangle} \xi(m_\star > 8\mathrm{M}_\odot) E_{\rm SN} \epsilon_{\rm SN}. \tag{3}$$

Here it is assumed that stars form following a universal Initial Mass Function (IMF in short), $\xi(m_\star)$; and that only stars with masses $m_\star > 8\mathrm{M}_\odot$ undergo SNeII during their last evolutionary stages. For simplicity we adopt an IMF given in [8], which gives a fraction of massive single stars $\xi(m_\star > 8\mathrm{M}_\odot) = 0.0037$ and a mean stellar mass $\langle m_\star \rangle = 0.4\mathrm{M}_\odot$.

On the other hand, the energy required to remove a DM cusp can be estimated as $\Delta E = \Delta W/2 = (W_{\rm core} - W_{\rm cusp})/2$, where W is the halo potential energy

$$W = -4\pi G \int_0^{r_{\rm vir}} \rho(r) M(r) r dr; \tag{4}$$

and $M(r)$ is the halo mass profile, which can be integrated analytically from eq. (1)

It is easy to show that the energy goes as

$$\Delta E = \frac{G M_{\rm vir}^2}{r_s} \Theta(x, c). \tag{5}$$

where $\Theta \sim x$ for $x \ll 1$, i.e. the amount of energy required to form small cores scales linearly with the core size; whereas for $x \gg 1$, this function approaches asymptotically the limit $\lim_{x\to\infty} \Theta \approx 0.05$.

Fig. 3 compares the amount of stars required to generate a core size $r_c = 1$kpc (denoted as $M_{\star,\rm core}$) as a function of satellite mass ($M_{\star,\rm sat}$), where the relation $M_{\star,\rm sat} = M_{\star,\rm sat}(M_{\rm vir})$ has been tuned to reproduce the number of visible satellites in the Milky Way [7]. We also set $\epsilon_{\rm SN} = 0.4$ to facilitate a comparison against the hydrodynamical simulations of [11]. Models that reconcile the 'missing satellite' *and* 'core/cusp' problems by suppression star formation obey the condition $M_{\star,\rm core} < M_{\star,\rm sat}$ and fall below the horizontal dotted line in Fig. 3. Notice that if DM cusps are removed by the time satellites are accreted ($z_{\rm core} = z_{\rm acc} \approx 1$; solid line) the presence of DM cores should be limited to galaxies with $M_\star > 10^{7-8}\mathrm{M}_\odot$, in good agreement with the hydro-dynamical simulations of [11].

Fig. 3 highlights a tension between CDM predictions and observations on small galactic scales. On the one hand, we find that the cored density profile measured in two of the brightest MW dSphs points toward an efficient conversion of primordial gas into stars in faint, low-mass galaxies ($M_\star < 10^7\mathrm{M}_\odot$). On the other, a strong suppression of star formation is required *on the same mass scales* in order to accommodate the small number of visible satellites with the halo mass function predicted by collision-less CDM simulations. Notice that although shifting the transformation to $z_{\rm core} \approx 6$ helps to accommodate DM cores in the bright dSphs (i.e. $M_\star > 10^6\mathrm{M}_\odot$), the tension cannot be completely eliminated but is simply shifted to lower luminosities.

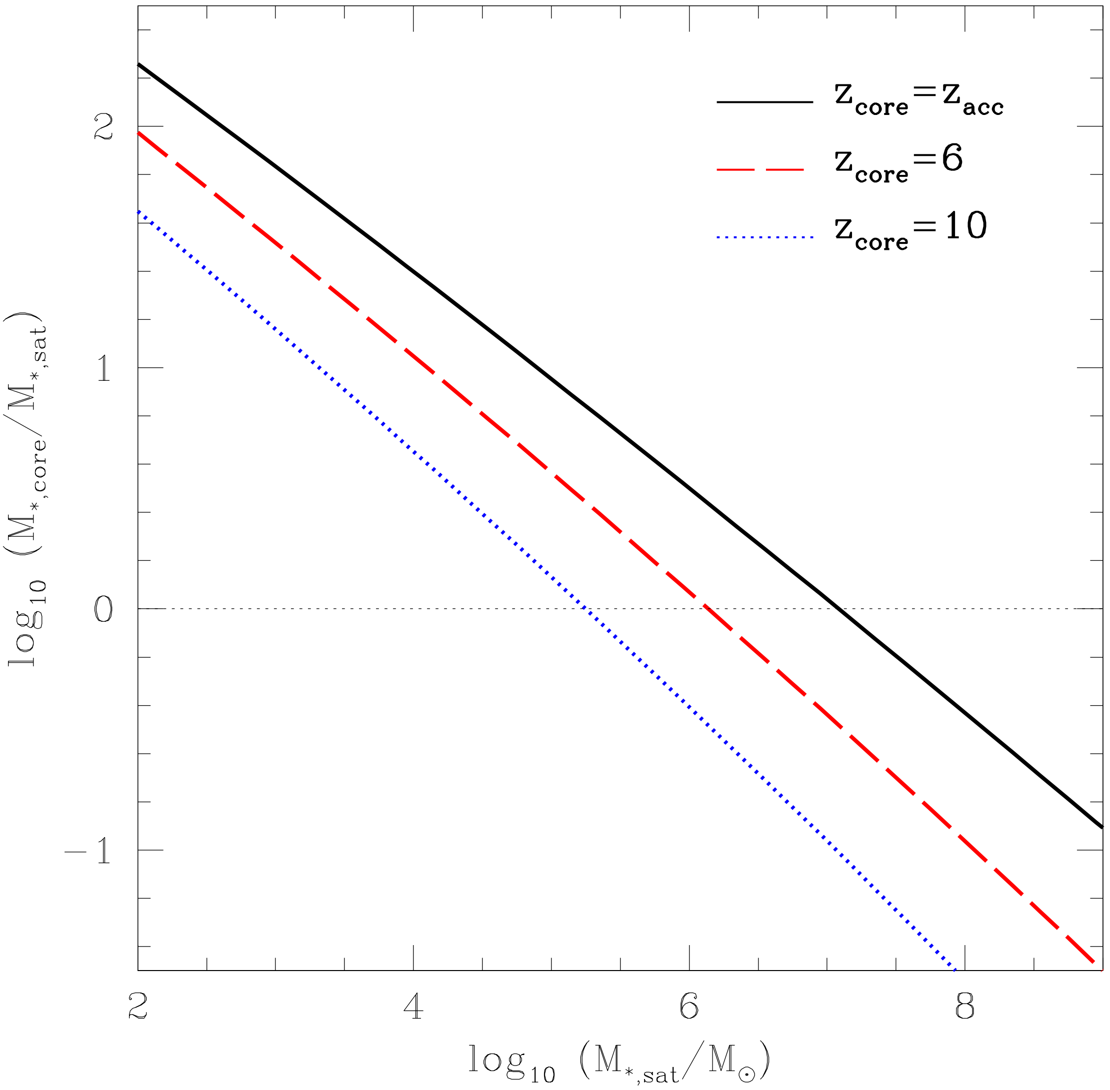

Figure 3: Minimum stellar mass required to form a DM core with $r_c = 1$ kpc, $M_{\star,\rm core}$, against the stellar mass tuned to reproduce the number of visible substructures in CDM simulations, $M_{\star,\rm sat}$. Solid lines show both quantities calculated at an accretion time $z_{\rm acc} = 1$, which roughly corresponds to the time at which the majority of the surviving satellites are accreted onto MW-like haloes. Dotted and short-dashed lines show how the stellar masses compare if the cusp removal is shifted to earlier times in the mass evolution of the satellites ($z_{\rm core} = 6$ and 10, respectively.)

4 Discussion

Recently, it has been shown [11, 23, 1] that violent SNeII feedback can remove cusps in galaxies with $M_\star > 10^8 \mathrm{M}_\odot$. Although these simulations were not able to reproduce WP11 results, these authors highlighted the importance DM cores for the hierarchical formation of galaxies such as the Milky Way. In particular, the fact that satellite galaxies embedded in cored DM halos are more prone to tidal disruption than those in NFW halos [18] was shown to introduce a strong selection bias in the surviving satellite population of Milky Way-like galaxies, where faint dSphs that retain their centrally-divergent DM profiles are more likely to survive than bright satellites embedded on cored halos moving on eccentric orbits. As a result, the formation of the stellar halo as well as the satellite luminosity function appears strongly linked with stellar feeback processes acting on dSphs at high redshifts.

Investigating the orbits of the satellite population in the Milky Way as a function of their luminosity thus provides an alternative observational approach to CDM problems on small scales. In particular, knowledge on the satellite orbits would allow us to relate the internal evolution of satellites with the hierarchical formation of our Galaxy. This topic will likely gain relevance in the next few years with the advent of Gaia, which will measure the orbits of satellite galaxies within the virial radius of the Milky Way with unprecedented accuracy.

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