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Baryonic solutions and challenges for cosmological models of dwarf galaxies

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Galaxies and their dark-matter haloes have posed several challenges to the dark energy plus cold dark matter (ΛCDM) cosmological model. These discrepancies between observations and theory intensify for the lowest-mass ('dwarf') galaxies. ΛCDM predictions for the number, spatial distribution and internal structure of low-mass dark-matter haloes have historically been at odds with observed dwarf galaxies, but this is partially expected, because many predictions modelled only the dark-matter component. Any robust ΛCDM prediction must include, hand in hand, a model for galaxy formation to understand how baryonic matter populates and affects dark-matter haloes. In this Review, we consider the most notable challenges to ΛCDM regarding dwarf galaxies, and we discuss how recent cosmological numerical simulations have pinpointed baryonic solutions to these challenges. We identify remaining tensions, including the diversity of the inner dark-matter content, planes of satellites, stellar morphologies and star-formation quenching. Their resolution, or validation as actual problems with ΛCDM, will probably require both refining of galaxy-formation models and improving numerical accuracy in simulations.

Baryonic matter constitutes only ~17% of the total mass budget in the Universe[1], but it dominates what we call galaxies in observations. Modelling the effects of baryons is therefore unavoidable in constructing a successful cosmological galaxy-formation theory to compare against observations[2,3]. The relevant physical processes in galaxies interact nonlinearly with each other and also may back-react onto the (dominant) dark-matter component through gravity. Cosmological numerical simulations have thus emerged as powerful tools to follow the assembly of galaxies within dark-matter haloes[4,5].

In this Review we focus on theoretical insights from cosmological baryonic simulations within the dark energy plus cold dark matter (ΛCDM) model on the formation of low-mass (dwarf) galaxies with stellar masses $M_* \lesssim 10^9$ solar masses ($M_\odot$). Other theoretical approaches, such as analytical/semi-analytical methods[6,7] and semi-empirical/forward-modelling techniques[8–13], are also immensely valuable and complementary, although we refer the reader to the references cited. Furthermore, in this Review we focus only on CDM as a viable dark-matter model. However, some tensions and challenges with observations might be mitigated, sometimes arguably more naturally, by changing the underlying nature of dark matter or modifying the law of gravity. We refer the reader to refs. [14–16] for a discussion of these approaches.

The physics of dwarf galaxy formation

The formation of dark-matter structures in ΛCDM is a process that is relatively well understood: haloes form from the hierarchical growth of high-density fluctuations in an otherwise homogeneous early Universe. Haloes assemble 'hierarchically': low-mass haloes collapse first and then merge to form more massive ones. Because CDM is assumed to be collisionless, only the effects of gravity are important to study the formation of dark-matter structures. Baryons, on the other hand, which were initially primordial gas but then (in part) converted to stars and metals, decoupled early from the dark matter; modelling their evolution requires a complex network of physical processes, including hydrodyamics and the cooling and heating of gas, in addition to gravity. We refer to these as baryonic processes.

Several baryonic processes are essential to form realistic galaxies within ΛCDM. One important aspect of their combined effects is a suppression of the efficiency of star formation, achieved by a combination of stellar feedback channels including supernova explosions[17–23] and radiation and winds from young stars[24,25]. Additionally, the extragalactic ultraviolet (UV) background, which drives cosmic reionization, suppresses gaseous accretion into galaxies. Although these processes all affect massive galaxies such as the Milky Way (MW), dwarf galaxies, with their shallower dark-matter potentials and lower numbers of stars, are particularly susceptible to the physics of stellar feedback and reionization. For instance, on the extreme scales of ultrafaint dwarf galaxies ($M_* \lesssim 10^5 M_\odot$; see ref. [14]), cosmic reionization is thought to halt star formation entirely, making such present-day galaxies 'fossils' of reionization[26–31]. Thus, dwarf galaxies are particularly sensitive laboratories for testing galaxy-formation models.

Environmental effects also shape the dwarf galaxies that orbit inside more massive host haloes, which for MW-mass haloes corresponds to distances of ~300–400 kpc. These 'satellite' dwarf galaxies show differences in their properties compared with 'isolated' (or 'field' or 'central') dwarf galaxies that are not embedded within a larger host halo. As they orbit, satellites experience substantial tidal stripping from the host halo potential, leading to significant mass loss[32,33]. This stripping proceeds primarily outside-in, so it initially impacts the more extended dark matter, only later affecting the more centrally concentrated (and more tightly bound) stars and gas in the galaxy[34–39]. Simulations typically find that present-day satellites of MW-mass haloes retain on average 20–40% of their initial dark-matter mass and $\gtrsim$75% of their stellar mass[40–42]. Eventually, the inner (luminous) region of a satellite can start to be stripped as well, which may help explain the kinematics observed for satellites of the MW[43–45].

After infall, the gas content of satellites may also be suppressed. First the host halo can prevent new accretion from the cosmic web, then, eventually, ram pressure via interaction with the host halo's

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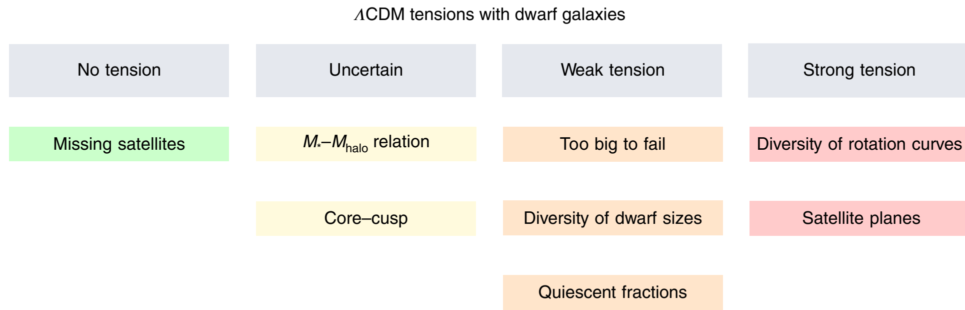

Fig. 1 | Historical and current tensions between ΛCDM theory and observations of dwarf galaxies. We classify these according to the level of tension/challenge they present to the cosmological ΛCDM scenario after the critical effects of baryonic physics have been considered. We discuss the M_*–M_{halo} relation and the too-big-to-fail (TBTF) problem in sections with those respective headings. We address the core–cusp problem and the diversity of rotation curves in the 'Dark-matter distribution within dwarf galaxies' section, the diversity of sizes in the 'Baryonic distribution within dwarf galaxies' section and satellite planes together with quiescent fractions in the 'Satellite dwarf galaxies' section.

gaseous corona can remove dense gas from a satellite[46,47], which in turn can turn off ('quench') star formation. Modelling of the gas content in satellite dwarf galaxies is necessary to produce realistic colour gradients, quiescent fractions and star-formation histories[41,45,48–54]. Additional environmental effects such as tidal heating[55], tidal stirring[56,57] and biased formation in the higher-density environment[54,58–60] may help explain the different range of stellar sizes and morphologies in satellites compared with similar-mass central dwarf galaxies.

Tensions and problems with ΛCDM

ΛCDM, a mature theoretical framework, has evolved through different phases and challenges. Our goal is to review historical so-called problems of ΛCDM on the scales of dwarf galaxies, describe how the additional computational modelling of baryonic physics at sufficiently high resolution has resolved or recast many of these problems and discuss ongoing challenges and sources of tension for models of ΛCDM that include baryonic physics. Thus, we seek to recast these historical problems in a more productive and rigorous context.

In our evaluation, strictly speaking, a legitimate problem between theory and observations exists only if (1) a theoretical model that includes the relevant physics makes a firm prediction, and (2) a robust observational measurement disagrees with this prediction at a meaningful level (several σ). In this sense, mere uncertainty—either in observations or theoretical predictions—does not a priori constitute a problem. Instead, uncertainty points towards interesting directions to pursue to test models more rigorously and assess whether a legitimate disagreement exists, given better observations, better theoretical understanding or both.

The most famous example of a problem that has now been resolved is 'missing satellites'[61,62]: dark-matter-only ΛCDM cosmological simulations of MW-mass haloes predict many more satellites (dark-matter subhaloes) than the number of observed dwarf galaxies around the MW or Andromeda (M31). In retrospect, several sources of uncertainty and incompleteness limited a robust comparison between theory and observations, including: (1) simulations not modelling the role of baryons in the formation of a MW-mass galaxy, (2) uncertainty in the relation between the dark-matter mass of a subhalo and its (observable) galaxy mass/luminosity, (3) limited numerical resolution and (4) observational incompleteness in the number of satellites around the MW and M31. Indeed, two decades later, progress in both observations—with discoveries of dozens of new faint satellites[63]—and improved theoretical models that directly predict observable properties of dwarf galaxies (such as stellar mass/luminosity) has shown that there simply is no missing satellites problem: current ΛCDM cosmological baryonic simulations at sufficiently high resolution are consistent (within reasonable theoretical and observational uncertainties) with the observed numbers of satellites around the MW and M31[41,44,45,64–68], as we discuss below.

That said, several ongoing challenges persist and need to be addressed, and we propose to recast these according to the degree of 'tension' between current theoretical predictions of ΛCDM that include baryons and robust observations of dwarf galaxies. In some cases, the baryonic solutions that address some of the traditional problems, such as missing satellites, might cause (or exacerbate) other tensions. In Fig. 1, we list both historical and new tensions with ΛCDM, categorizing them by our evaluation of their current severity. We discuss them individually below.

The M_*–M_{halo} relation of dwarf galaxies

The ΛCDM model makes clear predictions for the mass function of dark-matter haloes[32,69]. Predictions for the counts of faint dwarf galaxies then follow from knowing the relation between stellar mass and halo mass. However, dark-matter halo masses are challenging to measure observationally. Instead, the luminosity and stellar mass functions of galaxies have been of paramount importance for validating cosmological models. However, the counts of ultrafaint galaxies (down to $M_* \approx 100$–$1{,}000\,M_\odot$) remain mostly unconstrained, even within the MW halo[63]. It is therefore still challenging to evaluate whether theoretical predictions agree with observations.

Alternatively, on just the theoretical side, one can compare the predictions of different simulations regarding the relation between galaxy stellar mass and dark-matter halo mass in the ultrafaint regime. Indeed, as discussed below, a careful look into state-of-the-art numerical simulations that predict the correct number of MW-like galaxies and classical dwarf galaxies suggests that their expected ultrafaint populations may differ, signalling an important theoretical uncertainty that persists. We thus emphasize that our discussion of this relation between stellar mass and dark-matter halo mass is different from the others in this Review because our comparison is only between different simulations, not (yet) between simulations and observations.

Figure 2 shows the relation between stellar mass and dark-matter halo mass, where we collect the present-day relation predicted from a sample of state-of-the-art cosmological simulations. Halo mass corresponds to the spherical radius within which the average density is 200 times the critical density, the so-called virial radius. Where a different definition of halo mass was presented in the published work, we converted those values using average mass–concentration relation from ref. [70]. In Fig. 2a, we include zoom-in simulations of MW-like or Local Group-like environments from various works: APOSTLE[44,71] from the EAGLE project[72], the Latte and ELVIS suites[45,65] from the FIRE-2 project[73], Auriga[74], NIHAO-UHD[41],

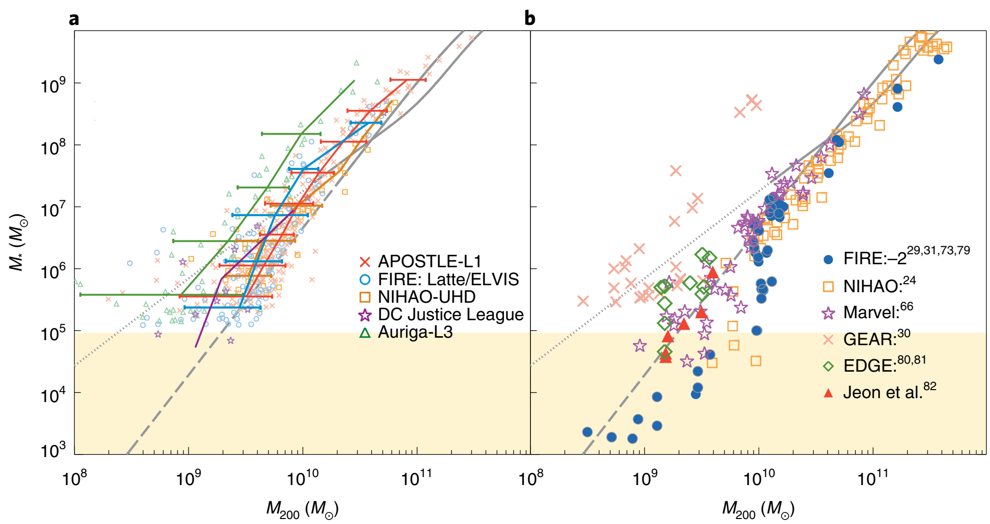

Fig. 2 | Relation between galaxy stellar mass and dark-matter halo mass. Central/field (non-satellite) dwarf galaxies in a sample of state-of-the-art cosmological simulations of galaxy formation are presented, as well as abundance-matching models shown by grey lines that are solid in the regime where they are constrained and dashed[77] and dotted[76] where they are extrapolated. Halo mass, M_{200}, is defined as the radius where the averaged density is 200 times the critical density of the universe. **a**, Central/field dwarf galaxies, beyond a MW-mass host halo, in simulations of MW-like or Local Group-like environments from various models: APOSTLE[44,71] (L1 resolution) from the EAGLE project[72]; the Latte and ELVIS suites[45,65] of FIRE-2 simulations[73]; NIHAO-UHD[41]; DC Justice League[66]; and Auriga[74] (L3 resolution). Corresponding coloured lines show the median halo mass at fixed stellar mass and the 10th–90th percentile range. We include simulated dwarfs with stellar masses above ~20 times the initial gas mass resolution corresponding to each simulation. **b**, Simulations that zoom in on individual dwarf-mass haloes: FIRE-2[29,31,73,79]; ref. [24] from NIHAO; refs. [80,81] from the EDGE project; ref. [30] using GEAR code; ref. [82]; and the Marvel simulations[66]. Note that the Marvel Suite simulates a zoom-in volume with several isolated dwarf haloes and therefore falls between the definitions for the left and right panels. The yellow shaded regions in both panels indicate the ultrafaint dwarf regime.

DC Justice League[75]; or zooms of relatively large regions, such as the Marvel Suite[66]. In all cases, we show only central (field) galaxies (not satellites) that are located beyond a MW-mass halo within the zoom-in region and therefore have not been stripped of mass as satellites have.

The numerical resolution of these simulations varies between gas particle masses of $\sim 10^3 M_\odot$ for the highest-resolution case (the Marvel Suite), $\sim 5\times 10^3 M_\odot$ for Auriga-L3 and FIRE-2 and $\sim 10^4 M_\odot$ for APOSTLE and NIHAO-UHD. The physics modelled and the particular implementation also vary from code to code; the differences in predictions are often impacted far more by these physics choices than by the numerical resolution. A detailed and fair account of the physics included in each simulation is beyond the scope of this Review, but each simulation included in Fig. 2 is a good example of the current state of affairs in galaxy-formation modelling, with demonstrated successes in the prediction of MW-like galaxies with realistic sizes, morphologies, kinematics, metallicities and star-formation rates, among other properties.

There is substantial overlap in the space spanned by different simulations, which is encouraging given the different codes and hydrodynamical solvers involved. In general, models approximately follow the extrapolations (dotted/dashed lines) from abundance-matching relations[76,77] calculated from more massive galaxies. However, in detail, the slope and the scatter for the stellar mass–halo mass relation may differ for each simulation. For instance, for a halo mass with $M_{200} \approx 3\times 10^{10} M_\odot$, simulations predict a dwarf galaxy within a stellar mass range spanning 1 dex of $M_* = 10^8$–$10^9 M_\odot$, despite the scatter intrinsic to each model being quite small for that halo mass. Conversely, for a dwarf galaxy with $M_* = [0.6, 1.2]\times 10^6 M_\odot$, the median halo masses predicted may differ by a factor of around four between different models. We caution that a tight relation between halo mass and stellar mass with small scatter, used for abundance matching of more massive galaxies, might not hold true for dwarf galaxies, where the scatter is expected to be larger[44,66,78]. However, this exercise highlights the level of variance expected in the stellar content at fixed dark-matter halo mass (and vice versa) between the different models.

Cosmological simulations can achieve higher resolution by zooming in on regions of individual dwarf galaxies instead of MW-like or Local Group-like hosts, which allows them to model the ultrafaint edge of galaxy formation. Figure 2b includes zoom-in simulations of individual dwarf galaxies from different codes: refs. [29,31,73,79] from FIRE-2, ref. [24] from NIHAO, refs. [80,81] from the EDGE project, ref. [30] using the GEAR code and ref. [82] using a modified version of Gadget-2. Despite the higher resolution, the differences between codes intensify, with the predicted stellar mass differing by more than ~2 orders of magnitude for halo masses $M_{200} \approx 10^9 M_\odot$ or a factor of ~10 in halo mass for $M_* \approx 10^6 M_\odot$. Although the small number of simulations and different accretion histories may help explain some of the differences, Fig. 2 confirms that the prediction for the relation between stellar mass and halo mass in the ultrafaint regime strongly depends on the simulation model. Therefore, ultrafaint galaxies persist as one of the most sensitive laboratories for any model of galaxy formation.

Beyond central galaxies, the stellar mass function of satellites also informs the stellar–halo mass relation, because the subhalo mass function (of haloes within a more massive host halo) is a clear prediction of ΛCDM[14,69]. All simulations in Fig. 2a predict realistic luminosity–stellar mass functions for satellite dwarf galaxies, at least at $M_* \gtrsim 10^5 M_\odot$, compared with observations (not shown here, we refer the reader to the original papers for details). The low efficiency of galaxy formation discussed above plays a crucial role in reproducing realistic numbers of dwarf galaxies from the steeply rising number of low-mass dark-matter haloes and subhaloes predicted in ΛCDM[61,62,69,83–85]. However, the uncertainty in the relation between stellar mass and halo mass implies a substantial uncertainty in the predicted counts of ultrafaint dwarfs galaxies within MW-mass analogues[66,78].

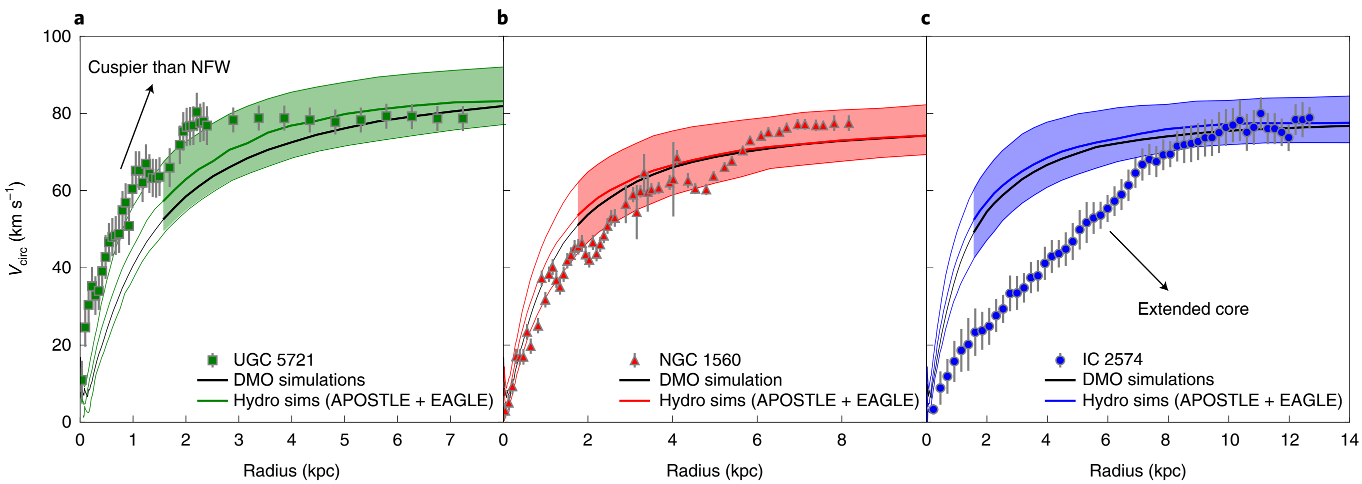

Fig. 3 | The diversity of rotation curves is a persistent challenge to ΛCDM. The observed rotation curves of dwarf galaxies show a wide range of shapes in their inner regions. **a–c**, Data from three observed dwarfs (symbols with error bars) with similar outer rotation velocities $V \approx 80\,\mathrm{km\,s^{-1}}$ but distinct inner behaviour are shown, from more steeply raising than NFW (**a**, UGC 5721) to well described by an NFW profile (**b**, NGC 1560) to a very extended core (**c**, IC 2574). Error bars account for statistical and systematic errors. Most baryonic simulations have been unable to consistently recreate the different velocity curve shapes in the inner regions without resorting to very strong observational biases. Thick coloured lines show the expectation (medians) from haloes in the maximum V_{circ} range of ~80–100 km s^{-1} in the APOSTLE and EAGLE baryonic (hydrodynamical) simulations with the thin lines and shading indicating the 10th–90th percentiles (the shading starts after the convergence radius, the minimum distance at which results are presumed to be reliable). For comparison, the black solid line shows a similar exercise using the dark-matter-only (DMO) version. Although different codes have reported successes in forming cores in the inner regions (see text for details), reproducing cores and cusps has remained a challenge for modern galaxy-formation simulations. Data from ref. [126].

A related aspect of models in the ultrafaint regime is the halo occupation fraction: the fraction of haloes at a given mass that host a galaxy (versus remain dark). The heating of gas from the UV background during the epoch of reionization is thought to prevent the formation of galaxies below a certain halo mass[86–90] while keeping the star-formation efficiency in ultrafaint galaxies low[29,91–93]. However, the details of reionization, including the speed (fast/slow), time (early/late) and mode (homogeneous/patchy), combined with the particular assembly history of low-mass haloes near the threshold of galaxy formation, create scatter in this transition from ultrafaint galaxies to completely dark haloes[29,80,81,94]. Interestingly, although some haloes might never have formed stars, they might still host gas in thermodynamic equilibrium with the cosmic UV background and therefore be detectable with atomic-gas surveys[95].

Current estimates for the maximum circular velocity below which haloes remain dark are $V_{circ} \leq 20\,\mathrm{km\,s^{-1}}$. However, given the strong additional tidal stripping from the MW[37,96–98], some works suggest that there are not enough subhaloes above that velocity scale to host the observed population of ultrafaint galaxies around the MW[13,99,100]. This implies a need for lower-mass haloes to form ultrafaint galaxies. In other words, modelling the additional tidal effects of the MW baryonic disk strongly strips (and can effectively destroy) dwarf galaxies with small pericentres, provoking a possible paradigm shift from the previous missing satellites problem to an opposite tension of 'not enough satellites'. However, in our evaluation this is not yet a robust tension with ΛCDM because these results require confirmation from higher-resolution simulations that are less affected by artificial numerical disruption[101–105]. This controversy shows that our understanding of the early Universe, and the formation of ultrafaint galaxies, is still actively developing. We therefore consider our understanding of the relation between stellar mass and dark-matter halo mass for dwarf galaxies to be 'uncertain', as we indicate in Fig. 1.

Dark-matter distribution within dwarf galaxies

Early CDM-only simulations revealed dark-matter haloes to be 'cuspy', with densities diverging as $\rho \propto r^{-1}$ (where r is radius) in the inner regions[106–108]. Once properly scaled, the density distribution of a halo of any mass can be parameterized by a single Navarro, Frenk and White ('NFW') profile with one free parameter[109,110]. Although improved numerical resolution suggested later that Einasto profiles with two free parameters[111] and an inner slope that asymptotically approaches $r^{-0.75}$ were a better description overall[112,113], cuspy NFW profiles are good enough representations of the halo regions accessible to galaxy observations[114].

This prediction is, however, often at odds with the slowly rising rotation curves observed in some dwarf galaxies, which suggest that their inner densities are more consistent with a constant-density 'core'[115,116]. This conflict became known as the core–cusp problem[117,118], and has commonly been identified in gas-rich dwarf galaxies with luminosities $L \geq 10^7\,L_\odot$ (where $L_\odot$ is the luminosity of the Sun). Cores are also inferred in some gas-free lower-mass satellite dwarf galaxies in the Local Group on the basis of the velocity dispersion of the stars[119–121], although the results remain controversial[122–124]. In practice, because measuring the exact shape of the mass profile in the inner region of the rotation/dispersion curve is challenging, it is more robust to phrase this as an 'inner-mass-deficit' tension[125–127]: CDM predicts more dark matter in the inner regions of dwarfs than is inferred from observations.

However, these are predictions from dark-matter-only simulations, and baryons can alter them. On the scale of dwarf galaxies, simulations show that stellar feedback can drive strong fluctuations in the gravitational potential by temporally driving gas out of the galaxy. Such potential fluctuations heat the orbits of dark-matter particles and effectively lower the density of dark matter on the scales of the galaxy[128–131].

This scenario has a few key requirements. The potential fluctuations need to be non-adiabatic[128], on timescales shorter than the dynamical/orbital time, to heat the orbits of dark-matter particles and move them to more extended (larger apocentre) orbits, flattening the inner cusp to a core[131]. Multiple 'blow-out' episodes are more effective than a single episode[20,130–133], which suggests that galaxies in which star formation proceeds in several consecutive bursts will probably have larger cores. However, burstiness alone is not a sufficient condition[134];

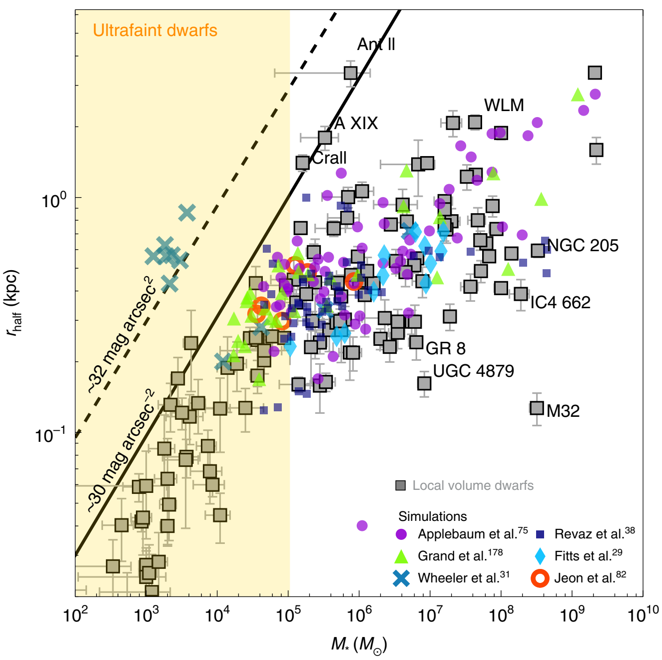

Fig. 4 | Dwarf galaxies show a wide range of sizes at fixed stellar mass. Current high-resolution simulations reproduce the general trend well, but each individual code shows too little scatter, leaving the diffuse and compact dwarfs under-represented in the models. The yellow shaded region indicates the ultrafaint dwarf regime. Grey squares show observational data in the Local Volume dwarfs from the updated catalogue of ref. [177] (satellites and field), with error bars estimated by Monte Carlo sampling assuming Gaussian errors plus error propagation on observational quantities. Antlia II data from ref. [297]. We assumed a mass-to-light ratio equal to 1 to compute stellar masses, and calculated the circularized half-light ratio from ref. [177] by multiplying the size along the major axis by $\sqrt{(1-e)}$, where e is the ellipticity of the system. Finally, we multiplied the circularized projected half-light radius by a constant factor (4/3) to estimate the three-dimensional half-mass radius (r_{half}) plotted. The names of some of the most extreme dwarfs are highlighted. Simulated data are shown by coloured symbols: DC Justice[75], Auriga-L2[178], FIRE[29], Gadget-2[82], FIRE low mass[31] and GEAR[30]. A minimum of 20 stellar particles apply to Auriga-L2 and GEAR simulations for which particle information was made available to us by the authors. The solid black line indicates ~30 mag arcsec^{-2}, approximately the surface-brightness limit in current ultrafaint dwarf surveys, which would mean objects as diffuse as those predicted by the FIRE-2 simulations (~32 mag arcsec^{-2}, dashed line) would go undetected[31].

gas should locally dominate the potential for a non-negligible time period before it is non-adiabatically expelled. This condition that is more easily satisfied if the density threshold for star formation used in a simulation is high enough[135–137], which is physically motivated, because most star formation is observed to occur only in self-gravitating, high-density, gas-like giant molecular clouds.

Subtleties in the numerical implementation of star formation and feedback, exacerbated by limitations in numerical resolution, have historically prevented rigorous modelling of core formation. Nearly all baryonic simulations that resolve and model star formation in high-density gas report some degree of core formation in the scale of 0.1–1 kpc in dwarfs[133,138–145]. However, three aspects of core formation remain controversial: (1) the link to the star-formation history, (2) the sizes of the cores and (3) the minimum mass to form a core.

On short timescales (≲200 Myr), the density slope of dark matter fluctuates between core-like and cusp-like as gas is expelled and re-cools/re-accretes into the galaxy, shallowing and deepening the overall potential, respectively. This means that gas-rich star-forming dwarf galaxies should show a diversity of inner-density slopes that correlate with recent star-formation activity[141,146,147]. On longer (cosmological) timescales, the degree of core formation increases with the number of starburst cycles, so dwarf galaxies with more extended star-formation histories should show more prominent cores[140,141,148,149]; observations indeed suggest this correlation[150]. Conversely, extended periods without star formation may lead to regrowth of a cusp[151]. However, not all simulations predict such a strong correlation[135] or the need for sustained active star formation to show cores[152].

The size of the dark-matter core in some simulations is linked to the half-mass radius of the stars[29,141,143], whereas controlled experiments suggest instead that the more concentrated the energy deposition of the feedback is, the more extended the dark-matter core[135,153]. With degeneracies in the baryonic modelling of galaxies going hand in hand with structural differences in the stellar component of the simulated galaxies[154–157], the predicted sizes of dark-matter cores remain a matter of debate.

Uncertainties also exist in the minimum galaxy mass needed for core formation. A balance between having enough star formation to affect the potential while still having a relatively low-mass dark-matter halo makes core formation from stellar feedback most efficient at masses comparable to the Large Magellanic Cloud, with $M_* \approx 10^9 M_\odot$ and halo masses ~$10^{11} M_\odot$ (refs. [138,139,141,142,144,158]). And although for fainter dwarfs this mechanism may lead to smaller and less-shallow cores, some analytical arguments imply no core formation in ultrafaint dwarfs[158], which agrees with many cosmological simulations that show a 'threshold' halo mass for core formation[29,140,159]. On the other hand, different simulation codes recently suggested that ultrafaint dwarfs should also harbour depleted dark-matter densities[152,160] as a combined result of feedback followed by minor mergers heating up the dark-matter component and an increased numerical resolution compared with previous simulations. The formation of cores all the way down to the ultrafaint regime also seems to be supported by analytical arguments[161], highlighting that the minimum mass for core formation from baryonic feedback remains open to debate and may be affected by numerical resolution effects.

With firm evidence from several independent numerical codes and analytical models showing that it is possible to form cores at the centres of the dark-matter haloes of dwarf galaxies from feedback effects, the core–cusp tension with ΛCDM is, at this point, only uncertain (as listed in Fig. 1) and awaits larger samples of observed dwarfs with better observations of their inner kinematics. On the theoretical side, a better understanding of the predicted core sizes, the correlations with other dwarf properties and the existence (or lack) of a threshold mass for core formation is also necessary.

However, a closer look into this core–cusp challenge using a compilation of available rotation curves of dwarf galaxies revealed a new (but related) and more challenging tension: observed dwarfs of similar masses ($M_* \geq 10^7 M_\odot$) show a large diversity in the inner shapes of their inferred dark-matter profiles: some are cored, some are consistent with NFW and some are even more concentrated than NFW profiles[126,162] (see Fig. 3 for an illustration). Moreover, a similar diversity in the dark-matter densities of MW satellites has also been found[163], with galaxies such as Draco consistent with a steep dark-matter cusp[164,165] that contrasts the large dark-matter core inferred for, for example, Fornax.

As discussed above, recent simulations have suggested that baryon-induced core formation is possible and common in dwarfs with medium to high masses. However, reproducing this diversity of rotation curves, mass ranges and, in particular, including their predicted correlations with other galaxy properties, remains troublesome with all current models[166] and therefore a strong point of tension between theoretical predictions of ΛCDM and observations.

Non-circular and out-of-equilibrium motions in observed rotation curves could cause, in principle, an inferred level of diversity similar to observations[127,146]. However, the needed perturbations to the velocity fields seem to be inconsistent with the well-behaved (regular) rotation curves measured. Overall, we must continue to proceed with caution and apply apples-to-apples comparisons of theory against observations, generating synthetic observations of simulations; for example, in dispersion-dominated galaxies, cusps can be disguised as cores in observations[123].

Finally, in the most extreme cases of diversity, some observed dwarf galaxies in fact seem to be baryon-dominated or dark-matter poor—such as DDO 50 and NGC 1613, in which the deficit of dark matter extends well beyond the radius of the stars, inconsistent with baryon-induced cores[167]. Examples of baryon-dominated inner regions have also been reported for dispersion-dominated dwarfs such as NGC 6822[168], the ultradiffuse galaxies DF2[169,170] and DF4[171] and Antlia II in our own Galaxy[172].

Barring significant systematics in the observations, the diversity of rotation curves (and enclosed dark-matter mass) is arguably one of the strongest current tensions with theoretical models without a clear and consistent baryonic solution so far[166,173]. In particular, it seems that the same baryonic feedback solutions that seem to solve some of the other tensions that we discuss in this Review also tend to lower the inner dark-matter density in dwarfs too uniformly. This behaviour warrants the classification of this tension as strong in Fig. 1.

Baryonic distribution within dwarf galaxies

We next discuss the baryonic components of dwarf galaxies, particularly stellar morphology, identifying an emerging tension: the simultaneous formation of both diffuse and compact dwarfs in simulations presents another manifestation of diversity in dwarf galaxies.

Most cosmological baryonic simulations of low-mass galaxies that couple star formation to high-density gas predict rapidly varying ('bursty') star formation[18,22,134,139,174], although the predicted level of burstiness differs across simulations[175]. Importantly, because both stars and CDM behave as (effectively) collisionless fluids, stars necessarily experience similar effects from the fluctuations of the gravitational potential induced by feedback as dark matter does, as we described above, with a 'breathing mode' of galaxy size fluctuations on short timescales and dynamical heating/puffing out on longer timescales[130,133,148]. Thus, the phenomenology for stars mirrors that for dark matter, as discussed above.

As a result of this dynamical heating process for the stars, simulations predict galaxies at $M_* \lesssim 10^9\,M_\odot$ to be mostly dispersion-dominated[147,176], which at least qualitatively agrees with observations. However, observed dwarfs display a wide range of sizes at a fixed stellar mass, as Fig. 4 shows for dwarf galaxies in the Local Volume from ref. [177] in grey (A. W. McConnachie, unpublished data), compared with several zoom-in simulations of MW-like haloes and their surrounding volumes[75,178] and zoom-in simulations of individual dwarfs[29–31,82]. These simulations model the average dwarf population reasonably well, but the intrinsic dispersion within each simulation set is appreciably smaller than in observations. In particular, diffuse dwarfs such as Crater II, Antlia II and Andromeda XIX, as well as compact dwarfs such as the dwarf elliptical M32, UGC 4879 and GR 8, are under-represented.

The problem of forming simultaneously diffuse and compact dwarfs may potentially worsen in simulations of higher-density environments such as groups and clusters, where diffuse, compact and ultracompact dwarfs appear in larger numbers[179–181]. Even within the Local Group, simulations in ref. [75] reported no significant issues with matching the most extended dwarfs, whereas several other codes (as shown by Fig. 4) have difficulties matching the most extended objects. In fact, dwarfs as extreme as Andromeda XIX or Antlia II are missing in all current simulations. Although artificial numerical disruption of such low-density systems may be a factor of concern, the systematic lack of diffuse objects in the simulations shown in Fig. 4 highlights the need for a better understanding of the physics that set the sizes of the most extended dwarf galaxies.

Some of the difficulties in simulating compact dwarfs may be naturally alleviated by reaching higher numerical resolution[75,178], such that numerical softening is at least an order of magnitude smaller than the galaxy itself, so the orbits of stars are followed with more fidelity. However, even some of the highest-resolution cosmological simulations, such as those in ref. [31], do not necessarily lead to smaller sizes. The problem is beyond the artificial softening of gravitational forces in these scales: with burstiness and its associated size fluctuations as inescapable predictions, it is difficult to envision how any compact stellar object can survive without dynamical heating and expansion in current baryonic treatments. Interestingly, ref. [75] traced the case of at least one compact dwarf formed with $M_* \approx 10^7\,M_\odot$ and half-light radii of only 40 pc to a heavily tidally stripped subhalo. However such a mechanism would not explain some of the compact objects in the Local Volume, such as UGC 4879 and GR 8, which are isolated from the MW and M31.

As with core formation, the predicted relation between stellar size/kinematics and star-formation history is observationally testable. Simulated dwarfs form stars at the highest rate during the gas-contraction phase, when their stellar sizes are small and velocity dispersions are high, while they expand their size in the gas-blow-out phase when stellar sizes are large and velocity dispersions are low[147,148]. Although existing observations do not support this correlation between stellar size and recent star-formation history[182], other observations do support the predicted relationship between kinematics and star-formation history[183,184].

One possible solution is to consider that burstiness might be overpredicted in current simulations. Attempts to compare predicted star-formation timescales to observations indicate that to first order they are consistent; for example, with predictions from the FIRE model[73,185]. However, some works indicate that simulated star-formation histories might be too bursty at $M_* \leq 10^{7.5}\,M_\odot$ (refs. [174,186,187]). Thus, although the intensity and frequency of star formation in dwarfs is not yet well constrained in detail by the models, the associated breathing mode seems fundamental to establishing the observed negative metallicity gradients[148,188] (at least in some models such as FIRE), dark-matter cores and even stellar haloes in dwarfs[189].

Understanding how to form compact stellar systems while simultaneously preserving the adequate level of burstiness to reproduce the observed properties of the more extended and less dense dwarfs remains a key challenge to galaxy-formation models within ΛCDM. We list the diversity of luminous sizes of dwarf galaxies as a weak tension in Fig. 1 and highlight that photometric/kinematic studies of individual stars in dwarfs, as well as integrated fluxes as proposed in ref. [186], might hold the key to observationally constraining how bursty star-formation histories are in dwarf galaxies.

The too-big-to-fail problem

As highlighted by refs. [190,191], the dark-matter mass—inferred indirectly from the stellar kinematics of stars within the half-light radius—for the most massive observed satellites of the MW is typically smaller than those of the massive subhaloes (which should then host these galaxies) of the simulated MW haloes in the Aquarius dark-matter-only simulations[69]. One solution is to require that several massive subhaloes ($V_{\rm peak} \gtrsim 30\,{\rm km\,s^{-1}}$, where $V_{\rm peak}$ is the maximum circular velocity across times for each subhalo) in simulations must be completely dark, but this is problematic because such subhaloes are massive enough that their gas should have cooled and formed stars; in other words, they are TBTF to host galaxies. Spectroscopic measurements of the stellar velocity dispersions of dwarfs in ref. [192] and ref. [193] argued for a similar TBTF problem in dwarf spheroidal

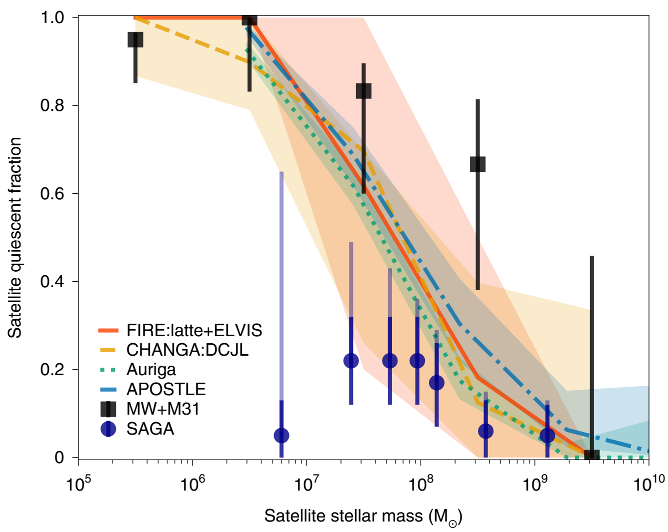

Fig. 5 | Fraction of satellite dwarf galaxies that are quiescent versus stellar mass in observations and simulations of MW-mass galaxies. Black data points show observed satellites around the MW and M31 (MW + M31), with data from ref. [253] updated using the observational compilation in ref. [254]. Blue points show observed satellites around 36 nearby MW-mass galaxies from SAGA[261]. In both cases, error bars show 68% uncertainties from observed counts, whereas for SAGA, lighter bars also show the maximal spectroscopic incompleteness correction in their survey. Coloured lines show simulations of MW-mass galaxies: FIRE-2 Latte + ELVIS suites[258,298] (shading indicates host-to-host scatter); CHANGA DC Justice League (DCJL) suite[255] (shading indicates scatter across hosts and satellite counts); Auriga and APOSTLE suites[64,256] (shading shows scatter from counts alone). At $M_* \gtrsim 10^9\,M_\odot$, both observed and simulated quiescent fractions broadly agree near 0. Down to $M_* \approx 10^7\,M_\odot$, all simulations lie between the MW + M31 and SAGA, although they agree better with the former. At $M_* \lesssim 10^7\,M_\odot$, all simulations predict quiescent fractions near unity, which agrees well with MW + M31 but is inconsistent with SAGA.

satellites of M31, noting that the more compact dwarf ellipticals do not suffer from this problem.

Although originally stated as a tension for satellites, the TBTF problem was found in central galaxies within the Local Group[194] and later generalized to other isolated dwarf galaxies in the nearby Universe for which analysis of their rotation curves indicated halo masses that are lower than predicted from abundance-matching relations[195,196]. This solidified TBTF as a tension in the field environment. Since the original discussion of the TBTF problem, several solutions have been proposed on the basis of the study of different cosmological simulations. We outline below the key proposed mechanisms to address the TBTF problem, some of which pertain only to the 'satellite' version of the problem.

First of all, the TBTF problem for satellites could be naturally alleviated, before invoking any baryonic effect, by lowering the mass assumed for the MW-mass host halo, given the predicted dependence of subhalo numbers on this in ΛCDM[197,198]. Although still within observational constraints, this solution then suggests that the true mass of the MW halo lies in the lower half of allowed estimates at present, which may conflict with the presence of a massive satellite such as the Large Magellanic Cloud or the large velocity of Leo I[199]. Halo-to-halo scatter on the subhalo content is also an important factor to consider[200,201]. For example, as shown in ref. [197], the Aquarius haloes used to first pose the TBTF problem all have above-average numbers of subhaloes. The extension of this argument also applies to the TBTF problem in the field in the Local Group, such that the number of haloes above a given mass threshold depends on the total mass of the Local Group, including mass outside the MW and M31 virial radii[202].

Considering baryons introduces several other solutions. First, as discussed earlier, most high-resolution baryonic simulations predict the formation of dark-matter cores, which alleviates the TBTF problem by reducing the dark-matter mass in the inner region without requiring dwarf galaxies (satellites or field) to reside in lower-mass haloes. This mechanism has been highlighted as contributing to the solution of the TBTF problem in the middle- to high-mass range of classical dwarfs, where core formation from baryonic processes is most effective[43,45,65,196,203]. Moreover, modelling the baryons in MW-like simulations revealed an important factor in resolving the TBTF problem in satellites: the gravitational potential from the central galaxy causes enhanced tidal stripping in satellites that is not present in dark-matter-only simulations, making subhaloes more susceptible to mass loss and enhancing disruption of dwarf galaxies[43,45,96,98,100,204–206]. This mechanism contributes to addressing the TBTF problem for satellites (but not in the field) at all masses, thus it is particularly important for low-mass dwarf galaxies, in which core formation is less efficient.

A more subtle factor to consider is that the total halo masses (or similarly V_{max}, the maximum circular velocity) of haloes (and subhaloes) in baryonic simulations are lower than their matched counterparts in dark-matter-only simulations. This is generally true regardless of whether the baryonic simulations produce dark-matter cores or not[43,207], for two reasons. First, the (external) UV background and (internal) stellar feedback remove a significant fraction of the baryons from $V_{max} < 50\,\mathrm{km\,s^{-1}}$ dwarf haloes. Second, this lower mass throughout most of cosmic time results in reduced cosmic accretion. This relatively small reduction in halo mass has a considerable effect on reducing the severity of TBTF for field and satellite galaxies, given the steep shape of the (sub)halo mass function[43,44,202].

In summary, there is a consensus among current cosmological simulations of MW/M31-mass haloes that there is no TBTF problem for MW and M31 satellites, regardless of whether the simulations produce cuspy or cored dark-matter profiles. We therefore report no apparent tension between observations and predictions in the context of TBTF for satellites in the Local Group.

However, the situation is less clear for the TBTF problem in the field. Several works have argued that alongside the baryonic effects discussed above, including an adequate comparison between simulations and observations that takes into account observational biases and techniques, is able to reconcile the predicted and observed velocity function of isolated gas-rich dwarfs as given by H I width data[208–211]. This solution to the TBTF problem in the field relies partially on the level of turbulence in the interstellar medium of dwarf galaxies, and also on the formation of dark-matter cores, the details of which (as discussed above) are not fully settled. Moreover, with large uncertainties in the incompleteness of data and total mass of the Local Group, it is not clear whether massive 'unaccounted-for' haloes in the Local Group field is a source of tension, and whether or not the predicted small-velocity dwarfs will be accounted for in upcoming H I observational surveys. There are still several observed dwarf galaxies with full rotation curve data, such as DDO 50 and IC 1613, among others[167,195], that suggest a dark-matter halo that is substantially less massive than predicted by abundance-matching models, along the direction of the original TBTF claims. More recently, several ultradiffuse dwarf galaxies in the field have also been found to have lower dark-matter masses than theoretically expected[212,213]. We therefore assess this problem as a weak tension in Fig. 1. Investigations into the diversity of rotation curves (or the core–cusp problem)—as well as the future discovery of nearby field dwarfs using upcoming surveys, such as the Rubin Observatory—will be fundamental to assess the level of tension, if any, with TBTF in the field.

Satellite dwarf galaxies in the Local Group and MW analogues

We finally review three other tests of simulation predictions for dwarf galaxies that are satellites around a MW-mass galaxy (within ~300–400 kpc).

A long-standing challenge for cosmological simulations has been achieving a sufficient resolution to model the spatial distribution of satellite galaxies within a MW-mass halo without suffering from artificial numerical 'overmerging'[33,61,102,214]. Cosmological zoom-in simulations that model only dark matter achieved high numerical resolution[69,215,216], but their lack of baryons and a MW-mass galaxy limited their accuracy[96,217–219]. Cosmological zoom-in simulations that include baryons now achieve sufficient resolution to match the radial distribution of satellite dwarf galaxies (at least at $M_* \gtrsim 10^5 M_\odot$) as observed around the MW, M31 and nearby MW-mass analogues[67,100,178,206,220]. Thus although efforts to gain detailed understanding of physical versus numerical effects remain ongoing and essential[102], in our evaluation current simulations of MW-mass galaxies show reasonable agreement with the observed radial distance distributions of satellite dwarf galaxies (although see ref. [221]).

More significant tension has persisted between simulations and observations regarding the three-dimensional spatial and three-dimensional velocity distributions of satellites. Nearly all of the satellites around the MW[222–226] and about half of the satellites around M31[227,228] are in a kinematically coherent, thin planar distribution. Some nearby galaxies show planar distributions of satellites as well, such as Centaurus A[229,230], M101[231] and the MATLAS sample of massive elliptical galaxies[232]. Many works have argued that the relative thinness of these satellite planes, and their kinematic coherence, strongly disagree with predictions from cosmological simulations, but have met with considerable debate[233–236].

The nature of these planes of satellites has persisted as one of the strongest tensions between theory and observations. Ref. [237] and ref. [238] provide extensive recent commentary on this topic; here we mention only two recently explored aspects that probably play an important role in comparing simulation predictions with observations of the MW and M31. First, simulations show that the presence of a massive satellite like the Large Magellanic Cloud (or M33/M32) can significantly boost the planarity of the satellite population[239] by accreting many satellites together in a similar orbit[240–244] and focusing the planarity of existing satellites[245]. Second, the planar structures of dwarf galaxies around the MW, M31 and the Local Group as a whole show some degree of alignment[246], which highlights the importance of modelling the larger-scale cosmological structure around the Local Group[220,247].

A compelling emerging tension for satellite dwarf galaxies regards their star formation and gas contents. Theory predicts that most dwarf galaxies with $M_* \gtrsim 10^{5-6} M_\odot$ retain their cold gas after cosmic reionization and thus remain star-forming[29], if they do not become a satellite in a larger (MW-mass) host halo. Indeed, nearly all observed isolated (non-satellite) dwarf galaxies are star-forming[248], with only three known exceptions[249–251]. Furthermore, nearly all dwarf galaxies in the Local Group beyond the halo radius ($\gtrsim$300 kpc) of the MW and M31 are star-forming; but, by contrast, nearly all satellites of the MW and M31 are quiescent, with no gas and no star formation[177,252–254].

This stark contrast for satellite versus central dwarf galaxies in the Local Group suggests that the environmental effects of a MW-mass halo are efficient at stripping gas (probably via ram pressure) out of satellites and quenching their star formation. Indeed, as Fig. 5 shows, current cosmological zoom-in simulations of MW-mass galaxies generally show efficient gas stripping and thus high quiescent fractions for satellites at $M_* \lesssim 10^8 M_\odot$, which are broadly consistent with the MW and M31[51,54,64,255–258]; although see ref. [259] for a different perspective.

However, recent observations of satellites beyond the Local Group suggest a strikingly different picture. The SAGA survey[260,261] has published quiescent fractions for 127 satellites at $M^* \gtrsim 10^7 M_\odot$ around 36 nearby MW-mass analogues—much more cosmologically representative than just the MW and M31 of the Local Group. As Fig. 5 shows, SAGA finds that nearly all satellites are star-forming, with only $\lesssim$20% quiescent at all masses they probe, significantly lower (even considering potential incompleteness effects) than the $\gtrsim$70% quiescent fractions at these masses around the MW and M31. At face value, these SAGA results upend the long-standing expectation that MW-mass haloes are efficient at stripping gas and quenching star formation in satellite dwarf galaxies.

As Figure 5 also shows, the quiescent fractions of satellites in SAGA data are substantially lower than all current cosmological zoom-in simulations at $M_* \lesssim 10^8 M_\odot$. One possibility is significant incompleteness of (diffuse) quiescent galaxies in the SAGA survey, as ref. [257] suggested; although, if true, this would seem to require the existence of quiescent dwarf galaxies at lower surface brightnesses than those observed in the Local Group. Taken at face value, the SAGA results imply a new tension: that simulations of MW-mass haloes are in fact too efficient at stripping star-forming gas out of satellite dwarf galaxies (as suggested by the simulation results of ref. [259]). Thus, these SAGA results raise new questions: why have the MW and M31 been so efficient at quenching star formation in their satellites? Is the Local Group a cosmological outlier in this sense? Do cosmological simulations overpredict the efficiency of gas stripping and star-formation quenching for satellites in a typical MW-mass halo?

In summary, simulations show reasonable agreement with the radial distance distributions of satellites, but as we list in Fig. 1, significant tension persists regarding the planarity of the three-dimensional distribution, and the quenching of star formation in satellites presents a new tension, although more work is needed to understand the uniqueness of the Local Group and the completeness of surveys such as SAGA.

Future challenges

Three factors will drive progress in the near future in theoretical studies of dwarf galaxies: (1) improvements in the numerical power of simulations, propelled by optimized codes and higher-performance computing clusters; (2) implementations of additional physics and improved implementations of processes already modelled in the interstellar medium of dwarf galaxies; (3) new observational constraints on the population and star-formation histories of dwarf galaxies on small timescales in both the early Universe and ultra-faint galaxies in the present day. These observations would include the detection and characterization of the population of completely dark (sub)haloes (without stars or gas), which is one of the strongest untested predictions of galaxy formation in ΛCDM plus baryons.

Improvements on numerical resolution importantly will enable the exploration of more diverse cosmic environments, including those of groups and galaxy clusters, where dwarf galaxies display more extreme ranges of star-formation histories and morphologies, including both a numerous population of ultradiffuse and ultracompact dwarfs. Mighty efforts are already underway[262–265], but higher resolution is desirable to resolve fainter dwarfs, along with their sizes and inner baryonic plus dark-matter structure.

Frontier simulations will include a richer set of physical processes. For example, feedback from black holes has been confirmed observationally in several dwarf galaxies with masses $M_* \approx 10^8$–$10^9 M_\odot$ (refs. [266–269]), while most simulations of dwarf galaxies do not include the physics of black holes (although some efforts are underway[270–273]). Magnetic fields and their interactions with cosmic rays probably affect the ability of dwarf galaxies to form stars and drive outflows[274–280], but these processes are only now starting to be modelled in dwarf galaxies, with significant numerical development to come. As telescopes peer deeper into the early

Universe, improved treatments for reionization and the evolution of the UV background, the effects of radiation via radiative transfer, low-metallicity star formation and the first generation (Population III) stars will become key to making robust theoretical predictions, especially for ultrafaint dwarf galaxies[82,281–285]. Alongside improvements in the physics, future studies should also address the effects of randomness and chaotic behaviour on solving the differential equations at the heart of simulations on the scale of dwarf galaxies[286,287].

Observationally, beyond a volume-complete census for fainter dwarfs being on the horizon with upcoming telescopes such as the Rubin Observatory, the Extremely Large Telescope or the Roman Space Telescope, measuring the satellite mass functions around low-mass primaries in the field may represent an attractive and more efficient alternative route to reach the regime of ultrafaint dwarfs where most theoretical predictions differ. In fact, because dwarf galaxies are also expected to host their own populations of satellites[79,288–290], and they are more abundant cosmologically than MW-mass galaxies, they might represent ideal candidates for surveys of their satellite contents and provide strong constraints for the abundance and properties of ultrafaint dwarfs. Several promising observational efforts on this direction might be able to add exciting constraints in the near future[291–295], which should inform current baryonic galaxy-formation models[296].

Dwarf galaxies stand strong as powerful cosmological probes. Contrasting their observed properties with baryonic simulations will continue to improve our galaxy-formation models and their numerical implementations. But dwarfs are also key to understanding the nature of dark matter: if the current tensions highlighted in this Review—and any still to be discovered in the future—remain unresolved by improved baryonic treatments coupled with a CDM scenario, the need for an alternative dark-matter model beyond ΛCDM will be made clear. Put differently, understanding and accurately modelling baryonic effects is a necessary prerequisite for any rigorous test of dark matter in the regime of dwarf galaxies.

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Competing interests

The authors declare no competing interests.

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