Cold dark matter heats up
Andrew Pontzen1,2,3 & Fabio Governato4

A principal discovery in modern cosmology is that standard model particles comprise only 5 per cent of the mass–energy budget of the Universe. In the ΛCDM paradigm, the remaining 95 per cent consists of dark energy (Λ) and cold dark matter. ΛCDM is being challenged by its apparent inability to explain the low–density ‘cores’ of dark matter measured at the centre of galaxies, where centrally concentrated high–density ‘cusps’ were predicted. But before drawing conclusions, it is necessary to include the effect of gas and stars, historically seen as passive components of galaxies. We now understand that these can inject heat energy into the cold dark matter through a coupling based on rapid gravitational potential fluctuations, explaining the observed low central densities.

Despite the unknown nature of the dominant components, the ΛCDM paradigm successfully describes the evolution of the Universe from its near-uniform early state, as measured by the cosmic microwave background1, to the present-day clustered distribution of matter in an accelerating Universe. Consequently, the properties of dark matter and the processes driving the formation and evolution of galaxies are fundamental, closely connected problems in modern astrophysics.

ΛCDM, through its explanation of observations on the largest observable scales, has been established as the standard cosmological paradigm. Over time, increasingly massive dark matter ‘halos’ form through gravitational instabilities, starting from small perturbations in the matter density field. It is within the gravitational potential of dark matter halos that galaxy formation—gas cooling and star formation—proceeds. However, long-standing problems have been encountered in reconciling the predictions of ΛCDM with observational results at galaxy scales. These problems probably stem from our poor understanding of the complex physics associated with star formation, and are complicated by our failure to identify the dark matter particle.

Recently, major progress has been made in addressing these discrepancies. We now understand that gas outflows from galaxies are ubiquitous, powered by energy released from stars and black hole accretion. These outflows change the distribution of the gas and stars that subsequently form. If the outflows launch at sufficient speed, they also cause an irreversible change in the dark matter distribution, even if the gas later returns to the galaxy in a ‘fountain’. The mechanism is purely gravitational and therefore independent of the nature of the particle. These processes fundamentally modify the structure of galaxies, and serve to bring theoretical expectations into agreement with previous problematic observational constraints. These astrophysical processes must therefore be fully understood before attempting to use galaxies to falsify ΛCDM.

Galaxy formation with cold dark matter

The viability of the ΛCDM picture of structure formation was first evaluated using computer simulations (allowing, for instance, neutrinos to be ruled out as the dominant component of dark matter4). Gas cooling and star formation within dark matter halos is now the standard paradigm for the origin of galaxies4. The behaviour of dark matter can be simulated on computers by chunking a portion of the universe into ‘particles’ and programming suitable physical laws to dictate how these particles move over time. Because simulated particles typically interact only through gravity, such simulations are called collisionless.

Early attempts used just 30,000 particles to follow large regions of the Universe. Consequently each particle had the mass of a large galaxy; even so, such simulations were expensive, taking 70 hours on state-of-the-art 3-MHz facilities. Such calculations would now take a few minutes on a mobile telephone. The growth of computing power and parallel capabilities meant that, by the 1990s, simulations became sufficiently powerful to make detailed predictions of the internal structure of halos in different cosmological scenarios. These simulations highlighted the universal nature of dark matter halos formed through collisionless collapse. The spherically averaged density of halos is ‘cusped’ at the centre (scaling approximately as ρ ∝ r−1, where ρ is the halo density and r is the radius from its centre), rolling to a steeper slope at larger radius (reaching ρ ∝ r−2); such behaviour is known as ‘NFW’, after the authors of a pivotal paper5.

At the same time, simulations started highlighting a number of deficiencies in the cold dark matter scenarios. The most evident was the overabundance, by more than an order of magnitude, of small satellites6 compared to the number observed orbiting the Milky Way at the time. Worse, the simulations significantly over-predicted the density of dark matter at the centre of galaxies7,8. Increasingly precise observations of the rotation curves of field galaxies have confirmed this discrepancy6 (see below).

Collisionless dark matter simulations have since reached maturity, with modern simulations using several billion resolution elements for just one Milky-Way-sized halo9–14. However, to make predictions that are testable against observations of the real Universe, baryon physics must be introduced. (Here we are adopting the astronomical convention of referring to baryons and leptons collectively as ‘baryons’. Because baryons dissipate energy and so collapse to smaller scales than dark matter, they constitute a sizeable fraction of the mass in the central regions of all but the faintest galaxies15. Moreover, observational constraints on galaxy formation ultimately come from photons, which can only be produced by baryons. Accordingly, much effort has recently been devoted to implementing gas hydrodynamics and a description of star formation within simulations9–19.

The energy released by young stellar populations and active galactic nuclei into the surrounding intergalactic medium is critical for regulating star formation1. Without this energy, most of the gas becomes cold and dense, rapidly collapsing to form stars, contradicting observations. Processes providing the energy to halt collapse are collectively named ‘feedback’ and include supernova winds, radiation from young stars, and radiation and heat from black hole accretion20–22. Including these effects...
has led to strides forward in forming realistic disk galaxies, reproducing the efficiency of star formation as a function of total galaxy mass, and linking gas accretion and mergers to galaxy morphology\textsuperscript{24–26}. However, until recently any direct effect of the baryonic component on the dark matter was limited to a minor ‘adiabatic’ correction\textsuperscript{27}. In this picture, the added gravitational attraction of gradually accumulating gas causes the dark matter to contract slightly. Star-formation processes resulted in ‘passive’ changes to the galaxy population—modulating the star-formation rate without significant changes to the underlying cosmic dark matter scaffolding.

This picture has recently been subverted. Spectroscopic observations reveal the ubiquity of massive galaxy outflows driven by feedback, carrying significant gas mass away from star-forming galaxies throughout cosmic history\textsuperscript{28–30}. It has slowly been realized that these directly observed processes have a non-adiabatic impact on the associated dark matter halos. The effect is to relieve discrepancies between baseline cold dark matter simulations and the real Universe. Our emerging understanding of these processes constitute the central part of this Review.

**Evidence that galactic gas is expelled**

There is clear observational evidence that star-formation activity drives gas out of galaxies (Fig. 1). This largely arises from studies of the resonance absorption lines imprinted into spectra by the presence of heavy elements. Consequently, dramatic advances in our knowledge have been made possible by 10-m-class telescope spectroscopy with instruments including the Keck telescope’s DEIMOS\textsuperscript{29} and LRIS\textsuperscript{31}. One can either look for blueshifted absorption in the spectra of galaxies themselves\textsuperscript{30,32} or at ‘intervening’ features imprinted on the spectra of more distant background light sources\textsuperscript{31}. A natural source for the energy required to generate these outflows are supernovae\textsuperscript{33} and ionizing radiation\textsuperscript{34} associated with stellar populations. In addition, energy released during accretion onto a massive central black hole may have a role, although the available energy is thought to scale steeply with the black hole’s mass, limiting these effects to the brightest galaxies or their progenitors\textsuperscript{35,36}.

Recent results underline the ubiquity of outflows\textsuperscript{37} from even the smallest objects (Fig. 1). Galaxies are surrounded by metal-enriched gas moving at hundreds of kilometres per second\textsuperscript{38} in bubbles extending to a hundred kiloparsecs or more. This result is exceptionally hard to explain without significant galactic winds. Mounting evidence also suggests that much of the in-falling material into galaxies may also be metal-enriched\textsuperscript{39}, consistent with a picture in which much of the wind does not attain the escape velocity but instead re-accretes\textsuperscript{40}.

A separate argument also points to the importance of winds during galaxy formation. Observed stellar profiles of small galaxies are mostly ‘bulgeless’, that is, well approximated by a disk of gas and stars with an almost exponential profile\textsuperscript{39,40}. Yet cosmological simulations show that the dark matter and baryons accumulated in all galaxy halos contain a large fraction of low-angular-momentum material\textsuperscript{41}—which would imply the presence of a bulge\textsuperscript{42}. This problem, known as the ‘angular momentum catastrophe’, is solved if low-angular-momentum gas is ejected\textsuperscript{14} by winds at relatively high redshift, when star formation peaks\textsuperscript{43}. Hence, the physics of galactic winds is of fundamental importance to understanding the population of disk galaxies, even before the effect on dark matter is considered.

**Evidence for a cusp–core discrepancy**

We now turn our attention to the excessive quantity of dark matter predicted by the cold dark matter model compared to measured densities in the innermost regions of galaxies.

**Dwarf galaxies**

As explained above, the under-abundance of dark matter in the centre of dwarf galaxies relative to theoretical predictions is known as the cusp–core discrepancy. The problem was discovered as soon as cosmological simulations became capable of predicting halo structure\textsuperscript{44,47}. Although acceptance was gradual, it is now firmly established that robust measurements of the dark matter density can be made from the rotation curves of gas-rich dwarf galaxies ‘in the field’ (that is, away from the influence of larger galaxies). In the innermost regions (of radius less than about half a kiloparsec) the baryonic contribution to the potential is comparable to that of the dark matter and must be subtracted\textsuperscript{12,48}. Consequently, inferring the dark matter density requires (1) high spatial resolution of the gas and stellar kinematics, (2) a comprehensive understanding of how to estimate and subtract the stellar and gas mass distribution from the central kiloparsec and (3) careful handling of systematic observational errors. The last category encompasses possible biases arising from radio beam-smearing, departure from circular orbits, centring difficulties, unknown details of stellar mass-to-light ratios and gravitational potential asphericity within galaxies; these are now thought to be under control, given that we can test algorithms on mock observations from simulations (where the true density is known)\textsuperscript{49–51}.

Results from recent surveys of the local Universe, such as THINGS and LITTLE THINGS\textsuperscript{52,53}, can therefore be regarded as free from significant observational bias. These samples reveal shallower-than-NFW dark matter profiles in a large fraction of dwarf field galaxies, with $r \propto r^{-0.4}$ interior to the central kiloparsec (Fig. 2). The objects are referred to as ‘cored’ although the estimated density profile is almost never actually flat. So, after 20 years of study, the cusp–core problem has remained a persistent and significant discrepancy between theoretical models of a ΛCDM universe and observations of dwarf galaxies.

**Milky Way satellites**

Small galaxies known as ‘dwarf spheroidals’ orbit close to the Milky Way. These dwarf spheroidals have little gas content and their stellar content is not in a rotational disk\textsuperscript{2}. This probably reflects the effect of tidal fields and strong interactions with the hot gas in the halo of the parent galaxy\textsuperscript{34}. Sampling the smallest halo masses in which galaxies form, these satellites have the potential to constrain the properties of
dark matter and the physics of galaxy formation and have accordingly received significant attention.

We discussed above how field dwarfs have been fundamental in revealing the apparent over-concentration of dark matter at the centre of halos. Satellite dwarfs, with an order-of-magnitude fewer stars, are potentially powerful probes of the dark matter distribution at the smallest scales. Various techniques hint at the existence of cores, rather than cusps, in the brightest dwarf spheroidals. However, because galaxy satellites do not possess atomic hydrogen disks and deviate from spherical symmetry, inferring the mass distribution of their dark matter halos involves different, less well-developed techniques than those applied to field galaxies. Rather than estimate the entire mass distribution, it is simpler to measure total mass inside the half-light radius (which typically lies at a few hundred parsecs). Compared to the most massive satellites in cold dark matter it is widely believed that there is too little mass in each real dwarf spheroid, a problem which is referred to as the "too big to fail," although the effect of tidal forces and stripping complicate the interpretation. At present, the properties and abundance of isolated, small field galaxies provide stronger constraints on models of feedback and alternative dark matter models.

High-mass galaxies

Field dwarfs typically fall into the category of 'low-surface-brightness' galaxies, defined by their extended diffuse stellar and gaseous disks. The uncertainties (discussed above) in recovering dark matter distributions in these objects are mitigated by the relatively small baryonic contributions to the potential at the time they are observed. A fraction of more massive galaxies (with rotational peak velocities larger than 100 km s$^{-1}$) also have these characteristics. Analyses of such galaxies again point to relatively flat central dark matter profiles. This is a significant finding because it shows that cores can be formed in halos with estimated stellar masses up to $5 \times 10^8 M_\odot$, where $M_\odot$ is the mass of the Sun.

The inner distribution of dark matter in galaxies with more conventional, massive disks (similar to our own Milky Way, for instance) is unfortunately harder to ascertain because the gravitational potential is more strongly dominated by baryons, so that uncertainties in the age, metallicity and hence light-to-mass conversion ratios of stellar populations dominate. However, many attempts have pointed to smaller central dark matter densities than theoretically expected, in line with the low-surface-brightness results. Some observations point to well-defined scaling laws that link the dark matter and baryon components, with dark matter and baryons following similar profiles. The significance of this relation is still very poorly understood, but it may point to a tight coupling between baryons and dark matter at galactic scales. More indirect constraints on the central dark matter densities in luminous galaxies arise from the existence of stellar bars that is, strong non-axisymmetric features in the distribution of stars in the dark disk), which, over cosmological timescales, seems dynamically incompatible with the presence of cuspy dark matter halos.

The largest bound systems in the Universe, galaxy clusters, have also attracted much interest in recent years as techniques to extract their density profile from lensing and kinematical data have developed. Subtracting the baryonic contribution to determine the presence of dark matter cusps or cores remains difficult, largely because of the unknown mass-to-light ratio of stars. As techniques mature further and sample sizes increase, this area will become increasingly important.

Gravitational disturbances to dark matter

We have outlined above the observational evidence pointing towards systematic departures of the distribution of dark matter from the original expectations of the cold dark matter paradigm. It has been widely suggested that this discrepancy could be addressed by gravitational interactions (the only way baryons and cold dark matter can interact) that transfer energy from the baryon component to the diffuse dark matter. If sufficient energy can be given gravitationally to dark matter particles in the centre of the halo, they will then migrate outwards, reducing the central density (note that this process will also apply to the stellar component). Energy can be transferred between these two components in two distinct ways: from the kinetic energy of incoming material or from baryonic processes linked to feedback within the galaxy. We will tackle these possibilities in turn.

As dense clumps move through a diffuse dark matter background a fraction of the orbital energy of the incoming material is lost to internal energy of the diffuse halo through "dynamical friction" (see Box 1 for an explanation). The sinking of dense gaseous or stellar clumps can flatten the central dark matter profile over a range of scales, although significant core creation has been demonstrated only in simulations of galaxy clusters rather than at the scale of individual galaxies. Dense, centrally concentrated baryons in infalling clumps are an essential prerequisite for this process.

The second class of energy sources comes from within the galaxy itself: energy liberated from stellar populations can be large compared to the binding energy of the galaxies. Early work suggested that removing most of the baryons in a rapid, dramatic starburst event could over-compensate for the previous adiabatic contraction, leading to the desired effect of reducing the central dark matter density. Subsequent studies examined the feasibility of this mechanism in more detail, showing in particular that repeated outflow episodes interspersed by re-accretion could have a cumulative effect on the dark matter.

However, these early investigations were limited by the unknown behaviour of gas in dwarf galaxies over cosmic time, and the lack of any clear analytic framework for understanding the apparently irreversible response of the dark matter. The outflows required seemed to redistribute a larger mass of gas than permitted by observations. It was unclear even to what extent the available energy in stellar populations couples to the gas through heating and radiation pressure; consequently the idea of energy transfer from baryons to the dark matter was not widely accepted at this stage.
Gas affects dark matter through gravity

**Box 1**

How repeated starbursts inside galaxies cause dark matter to migrate outwards, generating a near-constant-density ‘core’.

Until recently, dark matter was widely thought to contract slightly in response to galaxy formation\(^{27}\). But the ‘adiabatic’ calculations giving this result assume that gas moves in gradual steady flows. If it instead arrives in discrete dense clumps, a gravitationally induced wake of dark matter pulls back on the clump. This gives a net transfer of energy from gas to dark matter, a transformative effect known as dynamical friction\(^{79,80}\). The assumptions underlying adiabatic modelling can also fail owing to outflows if these evacuate gas at speeds significantly exceeding the local circular velocity\(^ {76,85}\). Moreover, this transfer is irreversible in the sense that re-accreting the lost gas does not lead to a compensating energy loss\(^ {76}\) (see Box 1 Figure). These results hold even if the gas never leaves the galaxy but is simply moved in bulk \(^ {76,86,87}\). The reason for this is as follows\(^ {76}\). Consider a dark matter particle that orbits close to the centre of the halo, where the gas is dense. If the gas is locally removed on a short timescale, the gravitational centripetal force holding the dark matter in its orbit is suddenly reduced in magnitude. The dark matter particle responds by flying outwards. Even if the gas later cools and settles back, the dark matter particle does not return to its original orbit. This is because the strength of gravity naturally declines with distance; once the particle has flown out to large distances, it is not possible to pull it back again. Repeating the process has a cumulative effect, which allows a significant transformation to be accomplished by recycling a small amount of gas instead of expelling an unfeasibly large amount of gas in one episode.

Other authors\(^ {86,87}\) showed that gas remaining fully within the system can still be effective in removing cusps when coupled to an energy source such as stellar feedback. For instance, supernovae driving gas on timescales close to the local orbital period were identified as a mechanism by which to transfer energy to dark matter particles\(^ {87}\). In this case, the cusps were destroyed in an energetically consistent manner without requiring any unrealistically dramatic outflows. By 2008 advances in numerical resolution and understanding of how gas cools before forming stars allowed for realistic treatments of the relevant hydrodynamics (Box 2). Simulations at high redshift\(^ {88}\) showed that dark matter could indeed be expelled self-consistently from the central regions of small protogalactic objects. This work provided the first proof-of-concept in a cosmological setting, but did not make predictions of observable objects (dwarfs are so faint that they are only observable in the nearby, redshift-zero Universe).

As it became possible to resolve star-forming regions\(^ {89}\) throughout the assembly of a dwarf galaxy from the young universe to the present day, for the first time simulations formed galaxies with stellar, gas and dark matter distributions consistent with observational bounds\(^ {44,90,91}\). Multiple short, locally concentrated bursts of star formation were the key new phenomenon enabling modification of the dark matter distribution: by temporarily evacuating gas from the central kiloparsec of the galaxy these cause dark matter to migrate irreversibly outwards\(^ {76}\); see Box 1. The actual process in play thus combines characteristics of the multiple-epoch outflow picture\(^ {86}\) and the internal-motions picture\(^ {87}\). It does not require fine-tuning of the gas velocity or dramatic evacuation of the gas from anything but the innermost region. The key requirement is that the gas must exit the centre of the galaxy at speeds greater than the local circular velocity.

Analytical modelling of multiple, impulsive changes to the gravitational potential gives considerable insight into how these changes arise and why they are irreversible\(^ {76}\). This allows for an accumulation of effects as the process repeats in several gas outflow events. In a single event the total gas mass in the galaxy limits the effect of outflows\(^ {83}\) but when the same gas is recycled and used in multiple events the only practical limitation is the total energy liberated from stellar populations and black holes (see below). The model of core creation through repeated outflows draws strong support from both analytical arguments\(^ {76}\) and from simulations using different numerical techniques\(^ {79}\). Observationally, dwarf galaxies, in which the evidence for cores is strongest, are observed to be gas-rich and show evidence for repeated small bursts and prolonged star-formation histories\(^ {92}\). This supports a picture in which the effect on the dark matter builds up over several billion years\(^ {76,85}\), during which gas is being cycled in repeating outflow and cooling episodes.

**Core sizes depend on galaxy mass**

A key part of confirming which mechanisms are responsible for flattened dark matter profiles is to predict and understand in detail how the processes affect systems of differing size. Building on the impulsive picture\(^ {86}\), full numerical simulations\(^ {89}\) and analytical arguments\(^ {87}\) have all pointed to a transition between core creation and persistent cusps below a critical stellar mass. This dividing line probably lies between \(10^7\,M_\odot\) and \(10^8\,M_\odot\) (assuming that most of the energy available from supernovae is transferred to the dark matter). For less massive stellar systems, the direct effects of stellar feedback on the dark matter should be minor on energetic grounds alone\(^ {86}\), as star formation becomes less efficient; see Fig. 3. The energetic argument shows that the possible cores from supernova feedback would be undetectably small for stellar masses significantly below \(10^8\,M_\odot\).

For stellar masses exceeding \(10^7\,M_\odot\), it is clear that energy from star-formation processes is available to alter the central regions of the dark
matters halo through sufficiently rapid galactic fountains or outflows, but few simulations of luminous galaxies reach the resolution necessary to study the formation of cores. Some high-resolution simulations of Milky Way analogues have been reported to form dark matter cores on scales of a kiloparsec or larger. On the other hand it has been reported that cores shrink with respect to the halo scale radius to push to 100\(m_n\) cm\(^{-3}\) or 100\(m_n\) cm\(^{-3}\), then a qualitatively different behaviour results. This is the density that corresponds to molecular cloud formation in our Galaxy, known to be the precursor of star formation. Instead of forming stars in a diffuse way through the entire disk, now stars form efficiently in small, isolated regions, which is considerably more realistic. When energy from the resulting stellar populations is dumped into the gas, the cloud heats to much higher temperatures than diffuse star formation achieves. It is likely that intense radiation pressure is also a significant factor. In any case, the gas is overpressurized by a factor of at least a hundred compared to its surroundings and expands rapidly. The combination of high initial density and explosive decompression is suitable for launching galactic-scale outflows; it is also what allows an efficient coupling of the available energy to dark matter (Box 1).

Modifying dark matter

We have established that there are many processes that can modify the dark matter distribution in the centre of galaxies, even if the dark matter is cold and collisionless (that is, interacts only through gravity)—a ‘minimal’ scenario motivated by supersymmetric weakly interacting massive particle physics scenarios with significant ‘dark sector’ interactions. However, these models do not produce cores on observationally relevant scales and are currently strongly constrained by the clustering of the neutral gas in the cosmic web.

Another major class, self-interacting dark matter (SIDM), refers to particle physics scenarios with significant ‘dark sector’ interactions. SIDM behaves more like a collisional fluid, preventing the central high-density cusp from forming and making the central regions more spherical. Unlike in the WDM case, the number density of dark matter halos remains relatively unchanged even at the smallest scales. The diversity of theoretical models, however, gives significant freedom in the choice of the cross-section and its possible dependence on particle velocity. This makes it difficult to establish a single baseline SIDM scenario.

The majority of work on non-minimal dark matter falls into the WDM or SIDM categories. However, modifications to the dark matter profile can also be achieved through other processes. For instance, particle–particle annihilations can reduce central densities directly, providing the physics is tuned to prevent rapid annihilation in the early universe. Alternatively, if dark matter decays over long timescales to slightly lighter daughter particles, the lost mass provides a source of kinetic energy for expanding the centre of dark matter halos. Another relevant possibility is that the dark matter is not formed from particles at all. In the case of an ultralight scalar field, for instance, the Compton wavelength becomes larger than the supposed interparticle separation; accordingly the field behaves as a Bose–Einstein condensate rather than as individual particles, preventing the central cusps from forming.

Figure 3 | Dark matter cores are only generated in sufficiently bright galaxies. Here we have plotted the power-law index \(\alpha\) of the dark matter density (as in Fig. 2, but here measured at radius 500 parsecs) against the mass of stars formed, \(M_*\) (updated from ref. 90). The expected slopes from pure dark matter calculations are approximated by the solid line (using the scaling relations from ref. 111), whereas hydrodynamic simulations at high mass have shallower slopes, indicated by the crosses. Large crosses show halos resolved with more than 500,000 simulated dark matter particles. Smaller crosses have fewer particles, but always more than 50,000. When less than about 10\(^6\)\(M_\odot\) of gas has formed into stars, there is insufficient energy available to flatten the cusp. The box symbols show data from the THINGS survey of field dwarf galaxies. Additional observational data at stellar masses lower than 10\(^6\)\(M_\odot\) would be highly valuable. This figure is updated from figure 1 of ref. 90.

Box 2

How to generate outflows

Outflows are probably generated by young stars inside galaxies. Computer simulations of the formation of galaxies would therefore ideally resolve cosmological large-scale structure (over tens of megaparsecs) down to the scale of individual stars (at least 10\(^4\) times smaller). This is, and seems certain to remain, unfeasible. The line of attack is instead to mimic the effects of stars without actually resolving them individually. Because star formation is the conclusion of runaway gas cooling and collapse, a typical computational approach is to form stars when gas satisfies certain averaged conditions, and in particular when it reaches a threshold density. As resolution slowly improves in simulations, smaller regions and larger densities can be self-consistently resolved. Until the mid-2000s, a typical threshold density was set at 0.1\(m_n\) cm\(^{-3}\), where \(m_n\) is the mass of a hydrogen atom. This corresponds to the mean density of galactic neutral atomic gas, so stars form throughout the disk of a simulated galaxy. Energy output from stars in the diffuse medium results in a gentle heating of the entire galaxy, slowing the process of further star formation. However, if one can achieve sufficient resolution (and implement the more complicated cooling physics required to push to 100\(m_n\) cm\(^{-3}\) or 100\(m_n\) cm\(^{-3}\), then a qualitatively different behaviour results. This is the density that corresponds to molecular cloud formation in our Galaxy, known to be the precursor of star formation. Instead of forming stars in a diffuse way through the entire disk, now stars form efficiently in small, isolated regions, which is considerably more realistic. When energy from the resulting stellar populations is dumped into the gas, the cloud heats to much higher temperatures than diffuse star formation achieves. It is likely that intense radiation pressure is also a significant factor. In any case, the gas is overpressurized by a factor of at least a hundred compared to its surroundings and expands rapidly. The combination of high initial density and explosive decompression is suitable for launching galactic-scale outflows; it is also what allows an efficient coupling of the available energy to dark matter (Box 1).
The discussion above is not intended to be exhaustive, but to indicate that there is no shortage of particle physics mechanisms that address the density of dark matter in galactic cores. However, unlike baryonic mechanisms, these do not simultaneously address the gas ‘angular momentum catastrophe’ discussed above. The angular momentum of gas arises from the gravitational collapse process, and so—in the absence of strong baryonic feedback—is fundamentally tied to the nature of large-scale structure rather than to details of the collapsed halos into which it flows. Given constraints from the distribution of intergalactic hydrogen, as seen through the Lyman-\(\alpha\) absorption in quasar spectra, permitted small-scale modifications to the power spectrum do not lead to structures with increased angular momentum\(^{19}\) and so cannot resolve the gas ‘angular momentum catastrophe’ discussed above.

This said, it would be foolhardy to proceed on the basis that cold dark matter must describe the correct fundamental particle physics. In particular, the effects of baryons may amplify or change the signatures of alternative particle models. The dwarf spheroidals teach us that different transformative mechanisms interact in surprising, nonlinear ways\(^{49}\), motivating detailed study of the galaxies formed in fully hydrodynamical simulations with exotic dark matter models\(^{19}\), a field that remains in its infancy relative to that of galaxy formation based on cold dark matter.

**Priorities for future work**

There are now plenty of known processes that can modify the distribution of dark matter, either by supposing non-minimal particle physics or by harnessing the power released by stars and black holes. The priority is to establish which of these are in play in the real Universe. Because the baryonic processes simultaneously modify a number of observational diagnostics (outflows, dark matter cores, stellar morphology and star-formation regulation), they weave into a coherent, testable framework. Additionally, to alleviate degeneracies between particle-physics-induced and outflow-induced modifications to cold dark matter, one can identify regimes in which only one or the other is active. This points towards the future value of careful studies probing scalings of cores from stellar masses below \(10^{11}\) \(\odot\) (where the energy available to create cores is so limited that baryonic effects are tightly constrained) to above \(10^{13}\) \(\odot\) (where a variety of processes are feasible).

It remains a possibility that tensions between observation and theory will begin to point unambiguously at exotic particle physics. Ultimately, this early paper clearly identified the ‘cusp’ in simulations of the behaviour of cold dark matter.

1. The Planck Collaboration et al. Planck 2013 results. XVI. Cosmological parameters. *Astron. Astrophys.* (in the press); preprint at http://arxiv.org/abs/1303.5076.
2. Blumenthal, G. R., Faber, S. M., Primack, J. R. & Rees, M. J. Formation of galaxies and large-scale structure with cold dark matter. *Nature* 311, 517–525 (1984).
3. Percival, W. J. et al. The 2dF Galaxy Redshift Survey: the power spectrum and the matter content of the Universe. *Mon. Not. R. Astron. Soc.* 327, 1297–1306 (2001).
4. White, S. D. M. & Rees, M. J. Core condensation in heavy halos—a two-stage theory for galaxy formation and clustering. *Mon. Not. R. Astron. Soc.* 183, 341–358 (1978).
40. Kormendy, J., Drnov, N., Bender, R. & Cornell, M. E. Bulgeless giant galaxies challenge our picture of galaxy formation by hierarchical clustering. Astrophys. J. 723, 54–80 (2010).
41. Barnes, J. & Efostarkou, G. Angular momentum from tidal torques. Astrophys. J. 319, 575–600 (1987).
42. van den Bosch, F. C., Burkert, A. & Swaters, R. A. The angular momentum content of dwarf galaxies: new challenges for the theory of galaxy formation. Mon. Not. R. Astron. Soc. 415, 1209–1215 (2011).
43. Binney, J., Gerhard, O. & Silk, J. The dark matter problem in disc galaxies. Mon. Not. R. Astron. Soc. 321, 471–474 (2001).
44. Governato, F. et al. Bulgeless dwarf galaxies and dark matter cores from simulations driven by supernova feedback. Nature 463, 203–206 (2010).
45. This work proposed, for the first time, a simulated dwarf galaxy with stellar and dark matter distribution consistent with modern day observations.
46. Brook, C. B. et al. Hierarchical formation of bulgeless galaxies: why outflows have low angular momentum. Mon. Not. R. Astron. Soc. 415, 1051–1060 (2011).
47. Frejaville, L. & Primack, J. R. Observational and theoretical constraints on singular dark matter halos. Astrophys. J. 427, L1–L4 (1994).
48. Moore, B. Evidence against dissipation-less dark matter from observations of galaxy haloes. Nature 370, 629–631 (1994).
49. These two papers (refs 46 and 47) pointed out the great difficulty in reconciling theoretical predictions of dark matter in dwarf galaxies with observations.
50. Simon, J. D., Bolatto, A. D., Leroy, A. Blitz, L. & Gates, E. L. High-resolution measurements of the halos of four dark matter-dominated galaxies: deviations from a universal density profile. Astrophys. J. 621, 757–776 (2005).
51. Swaters, R. A., Madore, B. F., van den Bosch, F. C. & Balcacels, M. The central mass distribution in dwarf and low surface brightness galaxies. Astrophys. J. 583, 773–791 (2003).
52. Oh, S.-H., de Blok, W. J. G., Brinks, E. & Walter, F. What is the dark matter profile of the Milky Way's dark matter halos? Mon. Not. R. Astron. Soc. 141, 193 (2011).
53. Oh, S.-H. et al. The central slope of dark matter cores in dwarf galaxies: simulations versus THINGS. Astron. J. 142, 24 (2011).
54. Walter, F. et al. THINGS: The H I nearby galaxy survey. Astron. J. 136, 2564–2647 (2008).
55. Hunter, D. A. et al. LITTLE THINGS. Astron. J. 144, 134 (2012).
56. Mayer, L. et al. The metamorphosis of tidally stirred dwarf galaxies. Astrophys. J. 519, 754–784 (2000).
57. Nierenberg, A. M. et al. Luminous satellites. II. Spatial distribution, luminosity function, and cosmic evolution. Astrophys. J. 752, 99 (2012).
58. Strigari, L. E. et al. A common mass scale for satellite galaxies of the Milky Way. Nature 464, 1096–1098 (2010).
59. Goerdt, T., Moore, B., Reader, J., Stadel, J. & Zemp, M. Does the Fornax dwarf spheroidal have a central cusp or core? Mon. Not. R. Astron. Soc. 368, 1037–1077 (2006).
60. Zolotov, A. et al. Bar- and baryon matter: why luminous satellite galaxies have reduced central masses. Astrophys. J. 761, 71 (2012).
61. Arakai, K., Klypin, A., More, S. & Trujillo-Gomez, S. Effects of baryon removal on the structure of dwarf spheroidal galaxies. Mon. Not. R. Astron. Soc. http://dx.doi.org/10.1093/mnras/stt279 (in the press); preprint at http://arxiv.org/abs/1121.6651.
62. Kupensarris, E., Martin, A. M., Giovannelli, R. & Haynes, M. P. The velocity width function of galaxies from the 40% ALFALFA survey: shedding light on the cold dark matter overabundance problem. Mon. Not. R. Astron. Soc. 422, 1231–1240 (2012).
63. Munshi, F. et al. Reproducing the stellar mass/halo mass relation in simulated dark halos: theory vs observational estimates. Astrophys. J. 766, 56 (2013).
64. McQuinn, K. W. B. et al. The nature of starbursts. I. The star formation histories of eighteen nearby starburst dwarf galaxies. Astrophys. J. 721, 297–317 (2010).
65. Peñarrubia, J., Pontzen, A., Walker, M. G. & Koposov, S. E. The coupling between the core/cusp and missing satellite problem. Astrophys. J. 759, 142 (2012).
66. Macciò, A. V. et al. Halo expansion in cosmological hydro simulations: toward a baryonic solution of the cusp/core problem in massive spirals. Astrophys. J. 744, 19 (2012).
67. Kuhlen, M., Guedes, J., Pillepich, A., Madau, P. & Mayer, L. An off-center density peak in the Milky Way’s dark matter halo? Astrophys. J. 765, 10 (2013).
68. Di Cintio, A. et al. The dependence of dark matter profiles on the stellar to halo mass ratio: a prediction for cusps vs cores. Mon. Not. R. Astron. Soc. 437, 415–423 (2014).
69. Martizzi, D., Teyssier, R., Moore, B. & Wetz, T. The effects of baryonic physics, black holes and active galactic nuclear feedback on the mass distribution in clusters of galaxies. Mon. Not. R. Astron. Soc. 432, 3081–3091 (2012).
70. Dalcanton, J. J. & Hogan, C. J. Halo cores and phase-space densities: observational constraints on dark matter physics and structure formation. Astrophys. J. 561, 35–45 (2001).
71. Menci, N., Fiore, F. & Lamastra, A. Galaxy formation in warm dark matter cosmology. Mon. Not. R. Astron. Soc. 421, 2384–2394 (2012).
72. Knebe, A., Devriendt, J. E. G., Mahmood, A. S. & Silk, J. Merger histories in warm dark matter galaxy structure simulations. Mon. Not. R. Astron. Soc. 325, 813–828 (2002).
73. Voel, M. Becker, G. D., Bolton, J. S. & Haehnelt, M. G. Warm dark matter as a solution to the small scale issue: new constraints from high redshift Lyman-α forest data. Phys. Rev. D 88, 043502 (2013).
74. Spergel, D. N. & Steinhardt, P. J. Observational evidence for self-interacting cold dark matter. Phys. Rev. Lett. 84, 3760–3763 (2000).
75. Peter, A. H. G., Rocha, M., Bullock, J. S. & Kaplinghat, M. Constraining self-interacting dark matter with the Milky Way's dwarf spheroidals. Mon. Not. R. Astron. Soc. 431, L20–L24 (2013).
105. Tulin, S., Yu, H.-B. & Zurek, K. M. Resonant dark forces and small scale structure. Phys. Rev. Lett. 110, 111301 (2013).

106. Kaplinghat, M., Knox, L. & Turner, M. S. Annihilating cold dark matter. Phys. Rev. Lett. 85, 3335–3338 (2000).

107. Peter, A. H. G., Moody, C. E. & Kamionkowski, M. Dark-matter decays and self-gravitating halos. Phys. Rev. D 81, 103501 (2010).

108. Sin, S.-J. Late-time phase transition and the galactic halo as a Bose liquid. Phys. Rev. D 50, 3650–3654 (1994).

109. Herpich, J. et al. MaGICC-WDM: the effects of warm dark matter in hydrodynamical simulations of disc galaxy formation. Mon. Not. R. Astron. Soc. 437, 293–304 (2014).

110. Christensen, C. et al. Implementing molecular hydrogen in hydrodynamic simulations of galaxy formation. Mon. Not. R. Astron. Soc. 425, 3058–3076 (2012).

111. Maccò, A. et al. Concentration, spin and shape of dark matter haloes: scatter and the dependence on mass and environment. Mon. Not. R. Astron. Soc. 378, 55–71 (2007).

Acknowledgements We thank S.-H. Oh, S. White, M. Pettini, C. Martin, M. Walker, J. Peña-Rib nackte, A. Brooks, T. Treu, R. Ellis, J. Wadsley and L. Randall for discussions and comments on an early draft. A.P. acknowledges support from the Oxford Martin School and Royal Society. F.G. acknowledges support from HST GO-1125 and NSF AST-0908499.

Author Contributions A.P. and F.G. jointly wrote the Review.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence should be addressed to A.P. (a.pontzen@ucl.ac.uk).