Administered by
Anatoly Klypin

Cume 358

(1) 10pt Using the information in the caption of fig. 1 and results in fig. 3, estimate the ratio of dark matter mass to the mass of baryons inside the 5 kpc radius for the galaxy.

Answer: The text states that 4 percent of the virial mass is in baryons (gas + stars). This gives the mass of baryons $M_{\rm bar} = ({\rm fraction-baryons}) \times M_{\rm vir} = 0.04 \times 3.5 \times 10^{10} M_\odot = 1.4 \times 10^9 M_\odot$. Because exponential scale-length of baryons is 0.9 kpc, most of the mass is within the central 5 kpc radius. Figure 3 gives rotational velocity of $V_{\rm rot} = 60$km/s at 5 kpc radius. Rotational velocity gives the total mass inside the radius: $V^2 = GM/R$. We get $M_{\rm tot}(R < 5kpc) = 4.15 \times 10^9 M_\odot$. This give dark matter mass inside the radius $M_{\rm dm} = M_{\rm tot} - M_{\rm bar} = 2.75 \times 10^9 M_\odot$. Thus the ratio of dark matter to baryon mass inside the 5 kpc radius is $M_{\rm dm}/M_{\rm bar} = 2$.

(2) 20pt Find the total number of supernovae occurred in that galaxy and estimate the total energy released by those supernovae into the ISM. Assuming that the energy is not radiated away, *is it enough to blow away the gas from that galaxy?* Energy of a single supernovae is $\epsilon_{\rm SN} = 10^{51}$ erg. It is mostly the kinetic energy of the debris of the explosion and it does not depend on the mass of the progenitor. Stars with mass larger than $10M_\odot$ explode as supernovae and most of them have mass about $10M_\odot$. For a realistic IMF, the fraction of mass of stars more massive than $10M_\odot$ is 10 percent. When estimating the binding energy, assume that the gravitational potential of gas in the disk is $\phi \approx -GM(R_{\rm out})/R_{\rm out}$, where $R_{\rm out} = 5$ kpc is the outer radius of the disk.

Answer: Life-time of a massive star, which explodes as SNII, is very short: 10-20 Myrs. As compared with the age of the galaxy, this is nearly instantaneous. At the same time, most of the stellar mass is locked in long-lived stars of one solar mass or less. There is some re-cycling of stellar mass (about 30 percent). For a more accurate estimate we would need to take this into account, but here we neglect it. Thus, the total stellar mass gives us a way to estimate the total number of supernovae over the history of the galaxy.

Because the text says that 70% of baryons is in gas, the rest of baryons is in stars: $M_* = 0.3 \times M_{\rm bar} = 4.2 \times 10^8 M_\odot$. The number of supernovae is

$$N_{\rm SN} \approx ({\rm Fraction-massive-stars}) \times M_*/({\rm Mass-one-SN}) = 4.2 \times 10^6. \quad (1)$$

The supernovae deposit

$$E_{\rm SN} = 4.2 \times 10^6 \times 10^{51} = 4.2 \times 10^{57}\ {\rm erg} \quad (2)$$

into the ISM. Gravitational binding energy is roughly $E_{\rm grav} = M_{\rm bar}\phi(5kpc)$, where grav.potential is defined by the total mass (mostly dark matter) within 5 kpc region: $\phi \approx GM(5kpc)/5kpc$. This gives $E_{\rm grav} = 10^{56}$ erg, which is enough to kick the gas from the central 5 kpc region of the galaxy if the energy is not lost. Most of the energy of SN is lost to radiation.

(3) 20pt Estimate the spin parameter of the whole galaxy (dark matter + gas + stars) within the virial radius assuming that before the baryons collapsed into the disk, they had the same rotation as the dark matter and that the angular momentum of the gas was preserved during the collapse. The spin parameter is the ratio of average rotational velocity to the circular velocity: $\lambda \approx < V_{\rm rot} > /V_{\rm circ}$. Because most of the mass in the halo and in the disk are at large radii, to simplify the calculations assume that baryons fell from the virial radius to the radius of 5 kpc.

Answer: First, we need to find how fast baryons rotated before the accretion. We use the conservation of angular momentum to find it: $V_{\rm before-accretion}R_{\rm before-accretion} = V_{\rm after-accretion}R_{\rm after-accretion}$. We know that after accretion (so, at present time) the rotation velocity is about 60 km/s (see fig.3). Radius before the accretion is the virial radius (100 kpc) and the radius at present is about 5 kpc. This gives the rotation velocity before the accretion: $V_{\rm before-accretion} = 60\ km/s \times (5/100) = 3$ km/s. The circular velocity at the virial radius is $V_{\rm circ} = \sqrt{GM_{\rm vir}/R_{\rm vir}} = 38.8$ km/s. Thus the spin parameter is

$$\lambda = \frac{< V_{\rm rot} >}{V_{\rm circ}} = 3/38.8 = 0.08, \tag{3}$$

which is almost three times larger than the typical spin parameter of a cosmological dark matter halo.

(4) 20pt The text says that the supernovae feedback results in formation of hot bubbles of the gas moving perpendicular to the disk with velocity of 100 km/s. We take a bubble at 1 kpc distance from the center and assume that the gas of the bubble moves away from the center without experiencing pressure forces with the gravity being the only factor, which slows it down. *Will the gas of the bubble escape from the galaxy?* You would need to estimate the gravitational potential of the galaxy at 1 kpc and at the virial radius (we assume that there is no mass outside of the virial radius). Note that gravitational potential of a system with distributed mass is *not* $GM(R)/R$. It is a work done by the force of gravity to move an object from one radius to another. Assume that starting with radius 1 kpc and all the way to the virial radius the mass is proportional to radius: $M(R) = (R/R_{\rm vir})M_{\rm vir}$ and the mass distribution is spherical.

Answer: We need to estimate the gravitational potential ϕ at 1 kpc radius. Once we have it, we can find the escape velocity, which is given by the condition that a particle of unit mass has zero energy: $\epsilon = V_{\rm esc}^2/2 + \phi = 0$. The gravitational potential is the work done by the force of gravity to move an object of unit mass from the given radius to infinity:

$$\phi(r) = -\int_r^\infty \frac{GM(r)}{r^2}dr = -\frac{GM(r)}{r} - \int_r^{R_{\rm vir}} \frac{GM(r)}{r^2}dr - \frac{GM(R_{\rm vir})}{R_{\rm vir}} \tag{4}$$

We use given approximation for the mass as the function of radius and notion of circular velocities:

$$|\phi(r)| = V_{\rm circ}^2(r) + V_{\rm circ}^2(R_{\rm vir}) + V_{\rm circ}^2(R_{\rm vir}) \ln\left(\frac{R_{\rm vir}}{r}\right) \tag{5}$$

Now we can find the total specific energy of the gas bubble:

$$\epsilon = \frac{V^2}{2} + \phi = \frac{V_{\rm gas}^2}{2} - V_{\rm circ}^2(r = 1kpc) - V_{\rm vir}^2\left[1 + \ln\left(\frac{R_{\rm vir}}{r}\right)\right] \tag{6}$$

Put numbers into the equation ($V_{\rm vir} = 38.8$ km/s, $V_{\rm gas} = 100$ km/s, $R_{\rm vir} = 100$ kpc) and find that the total energy is *negative*: the gas is not blown away from the galaxy, though it can move to quite a large distance from the center.

(5) 10pt The exponential scale-length and the rotational velocity of the galaxy are $R_d = 0.9$ kpc and $V_{\rm rot} = 60$ km/s. How does is compare with the Milky Way Galaxy? What are those parameters for the MW?

Answer: For our MW $R_d = 2.5 - 3$ kpc and $V_{\rm rot} = 220 - 230$ km/s

(6) 10pt What is the morphological type of the galaxy discussed in the paper? Sure, it is a dwarf, by what type? What types of dwarfs do you know?

Answer: This a dwarf irregular galaxy. Other types of dwarfs: dwarf spheroidal and dwarf elliptical.

(7) 10pt The abstract and introduction mention that the dark matter has "cuspy profile". How steep is the central cusp for a dark matter halo predicted by the standard cosmological model? What is the dark matter profile of a typical dark matter halo?

Answer: The standard cosmological model predicts the asymptotic value $\alpha = -1$ for the power-law slope of the density profile at the center of dark matter halos. Overall the following Navarro-Frank-White (NFW) approximation provides a very good fit for the density profiles:

$$\rho(r) = \frac{\rho_0}{x(1+x)^2}, \qquad x \equiv \frac{r}{r_s}, \tag{7}$$

where ρ_0 and r_s are two free parameters.

Relations and constants

- Gravitational constant $G = 6.674 \times 10^{-8} \quad cm^3/s^2/gram$
- $1pc = 3.08 \times 10^{18} \quad cm$
- $M_\odot = 2 \times 10^{33}$ gram
- Virial mass and radius for the galaxy discussed in the paper are $M_{\rm vir} = 3.5 \times 10^{10} M_\odot$ and $R_{\rm vir} = 100$ kpc.

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LETTERS

Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

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For almost two decades the properties of 'dwarf' galaxies have challenged the cold dark matter (CDM) model of galaxy formation[1]. Most observed dwarf galaxies consist of a rotating stellar disk[2] embedded in a massive dark-matter halo with a near-constant-density core[3]. Models based on the dominance of CDM, however, invariably form galaxies with dense spheroidal stellar bulges and steep central dark-matter profiles[4–6], because low-angular-momentum baryons and dark matter sink to the centres of galaxies through accretion and repeated mergers[7]. Processes that decrease the central density of CDM halos[8] have been identified, but have not yet reconciled theory with observations of present-day dwarfs. This failure is potentially catastrophic for the CDM model, possibly requiring a different dark-matter particle candidate[9]. Here we report hydrodynamical simulations (in a framework[10] assuming the presence of CDM and a cosmological constant) in which the inhomogeneous interstellar medium is resolved. Strong outflows from supernovae remove low-angular-momentum gas, which inhibits the formation of bulges and decreases the dark-matter density to less than half of what it would otherwise be within the central kiloparsec. The analogues of dwarf galaxies—bulgeless and with shallow central dark-matter profiles—arise naturally in these simulations.

In an expanding ΛCDM Universe (the favoured theory of cosmic structure formation), galaxy disks form as gas cools and collapses inside spinning halos of collisionless dark matter, reaching centrifugal equilibrium and turning into stars[11]. Models that assume that the stellar component of galaxies inherits the angular momentum distribution of their host dark-matter halos also predict the formation of a centrally concentrated stellar bulge and a cuspy dark-matter profile[7,12]. In contrast, the vast majority of dwarf galaxies have no stellar bulges, and the observed rotation curves of small galaxies often rise almost linearly in the central kiloparsec, a result interpreted as a sign of a shallow dark-matter distribution[13,14]. This excess of low-angular-momentum material creates the so-called 'angular momentum problem'[15] for CDM models.

A proposed solution to the existence of bulgeless galaxies invokes gas winds created by multiple supernova explosions to remove selectively low-angular-momentum baryons from the centre of galaxies[16]. Supernova winds are observed in both local and high-redshift galaxies and are efficient at removing gas from the disks of nearby galaxies at a rate of a few times the current star-formation rate[17,18]. Modelling the formation of a highly inhomogeneous multi-phase interstellar medium is necessary to tie star formation to high-density gas regions and to create supernova winds able to affect the internal mass distribution of galaxies[19,20]. Such numerical schemes for star formation and resulting feedback have been applied to the formation of high-redshift protogalaxies, leading to significant baryon loss and less concentrated systems[8,20]. Similarly, dynamical arguments[21,22] suggest that bulk gas motions (possibly supernova-induced) and orbital energy loss of gas clouds due to dynamical friction can transfer energy to the centre of the dark-matter component. Sudden gas removal through outflows then causes the dark-matter distribution to expand. These mechanisms were demonstrated to operate effectively in small high-redshift halos of total mass around $10^9 M_\odot$ ($M_\odot$ is the mass of the Sun) where they create small dark-matter cores[8]. However, such methods and the required high resolution have not been applied to cosmological hydrodynamical simulations of present-day dwarf galaxy systems ($V_{rot} \approx 60\,km\,s^{-1}$). Showing that the properties of dwarf galaxies can be accurately predicted by the CDM scenario would end the 'small scale crisis' and further constrain the properties of the dark-matter particle candidate.

To study the formation of dwarf galaxies in a ΛCDM cosmology, we analyse a novel set of cosmological simulations. Baryonic processes are included, as gas cooling[8], heating from the cosmic ultraviolet field[23], star formation and supernova-driven gas heating (Fig. 1). The resolution is such that dense gas clumps as small as $10^5 M_\odot$ are resolved, similar to real star-forming regions[19]. Hence, stars are allowed to form only in cold gas regions with a local density higher than 100 atomic mass units per cm^3, reflecting typical conditions in real galaxies. This description of star formation is a critical improvement over many previous cosmological simulations, in which star-forming regions were not individually resolved. We analysed a single dwarf galaxy (DG1), but we obtained equivalent results with galaxies of similar mass and different assembly histories and halo spin (another simulated galaxy is described in the Supplementary Information). DG1 has a rich merger history: three proto-galaxies of similar mass merge at redshift $z \approx 3$, and a large satellite is accreted at $z \approx 1.2$ that has a mass one-third that of the central galaxy (a 'major' merger). Several other satellites are accreted, including one at low redshift. Star formation occurs in bursts as observed in nearby dwarfs[24] peaking at $0.25 M_\odot\,yr^{-1}$ during interactions at $z \approx 2$. The disk component assembles shortly after that (Fig. 1a and b). At $z = 0$ an exponential stellar disk is surrounded by a neutral hydrogen (H I) disk that extends out to six disk scale lengths. The galaxy shows no sign of a stellar spheroid (Fig. 1d). The star-formation rate declines after $z = 1$, and at present it is down to $0.01 M_\odot\,yr^{-1}$, in agreement with galaxies of similar magnitude.

Supernova feedback creates holes in the H I distribution owing to bubbles of hot gas expanding perpendicularly to the disk with velocities approaching $100\,km\,s^{-1}$ (Fig. 1a). The H I super shells close to

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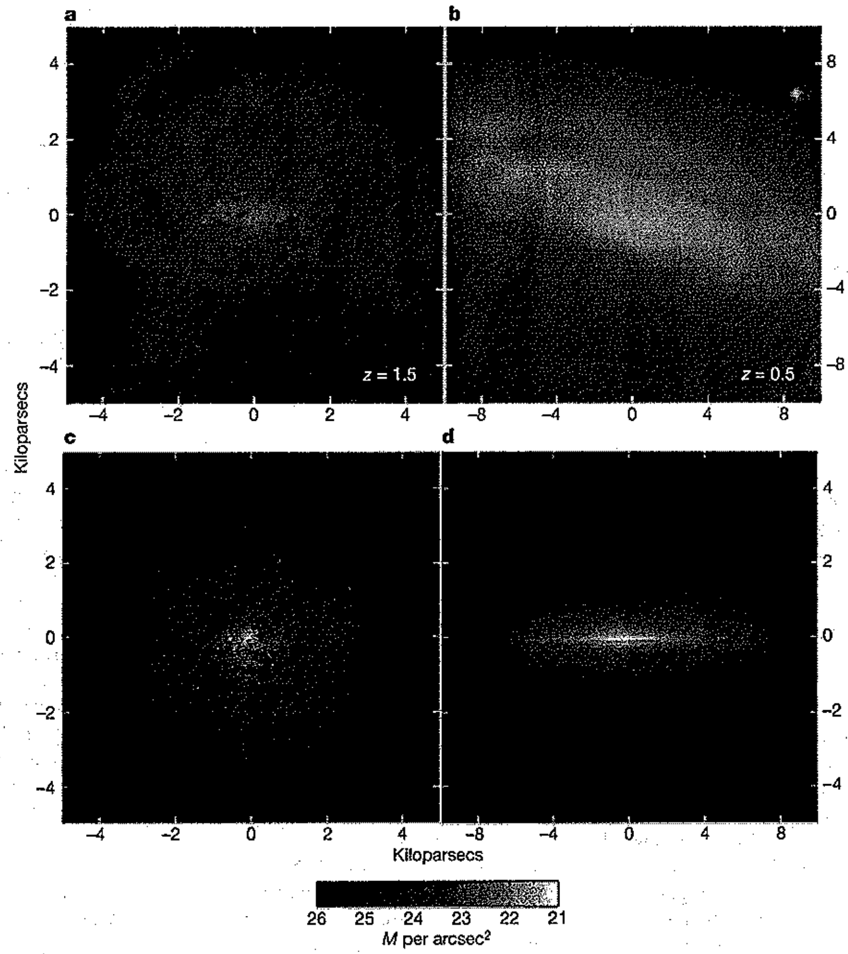

Figure 1 | The observable properties of simulated galaxy DG1. **a**, Colour-coded density map of the gas distribution at $z = 1.5$, showing the gas outflows and super shells. Distances on the axes are relative to the dark matter density maximum. **b**, The gas distribution at $z = 0.5$ when the disk has fully formed (note the larger scale). At $z = 0$ the total mass of the system within the virial radius is $3.5 \times 10^{10} M_{\odot}$. As a result of outflows and inefficient star formation, the disk (including H I gas and stars) to virial mass ratio is only 0.04, 70% of the disk mass is H I, and the $M_{\mathrm{HI}}/L_{\mathrm{B}}$ ratio is 1.2 (where L_{B} is the luminosity in the B band). The amount of baryons within the virial radius is only 30% of the cosmic fraction. These values are consistent with those observed in real galaxies of similar mass[7]. **c**, The face-on light distribution at $z = 0$ in the Sloan Digital Sky Survey (SDSS) *i* band. **d**, The galaxy seen edge-on in the same band. The effect of dust absorption is included. The total magnitude of the galaxy in the *i* SDSS band is −16.8, giving an *i* band *M/L* ratio of ~20. The galaxy $g - r$ colour is 0.52, typical of star-forming dwarf galaxies[27]. The rotation velocity is ~55 km s^{-1}, as measured using the $W_{20}/2$ linewidth (where W_{20} is the H I 21-cm linewidth in kilometres per second at 20% of maximum brightness for the galaxy observed). This simulation resolves the internal structure of galaxy DG1 with several million resolution elements, achieves a mass resolution of $10^3 M_{\odot}$ for each star particle and a force resolution of 86 parsecs. In the Supplementary Information we show that high resolution coupled with star formation being spatially associated to small gas clouds is a fundamental requirement for supernova feedback to generate outflows and lower the density at the centre of galaxy halos. Simulations using the same implementation of star formation and feedback reproduce some global scaling properties of observed galaxies across a range of masses and redshifts[29,30].

the disk plane are typically a few hundred parsecs wide, expanding at 10–30 km s^{-1}, similar to those observed in dwarfs[25]. Star formation happens in short, spatially concentrated bursts including several coeval star particles, so the typical energy per unit mass released in the surrounding gas is sufficient to disrupt gas clouds and generate gas fountains that unbind gas from the shallow potential of the galaxy at 2–6 times the instantaneous star-formation rate, consistent with observations[17]. As predicted in earlier studies[20], feedback from spatially resolved star formation results in a realistic low star-formation efficiency and a total baryon mass loss equal to a few times the final amount of stars. Star-forming regions are centrally biased or rapidly sinking to the galaxy centre owing to dynamical friction, so most of the gas becoming unbound is preferentially removed at small radii and at $z > 1$.

Mock images[26] (Fig. 1c and d) show that in redder bands the optical disk is relatively featureless, although star-forming regions are visually associated with short-lived spiral arms. The striking feature of this galaxy is the complete absence of a stellar spheroid even when observed edge-on (Fig. 1). The radial light distribution in all optical and near-infrared bands has an almost perfect exponential profile (Fig. 2), as is observed in dwarf galaxies. This galaxy would thus be classified as "bulgeless"[2], that is, lacking a visible central stellar spheroid. The formation of a pure disk galaxy with structural properties typical of observed gas-rich dwarfs[27] is a fundamental success of this set of simulations.

The underlying dark-matter and baryonic-mass profile of DG1 has been measured using kinematic estimators. The rotation curve of DG1 (Fig. 3) was obtained measuring the rotational motion of cold ($T < 10^4$ K) gas as a function of radius using the 'tilted ring analysis', which reproduces the effects of observational biases such as disk distortions and warping, bars and pressure support from non-circular motions[28]. The rotation curve of DG1 rises almost linearly out to one stellar disk scale length, and is still rising at four scale lengths (~4 kiloparsecs), similar to the rotation curves of real dwarf

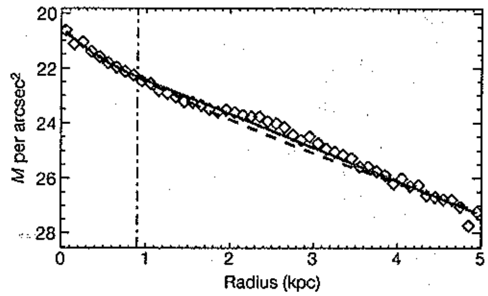

Figure 2 | The SDSS *i*-band radial light profile of the simulated dwarf galaxy DG1 at $z = 0$. Because it is less sensitive to recent star-formation events, the *i* band is often used to describe the underlying stellar mass distribution. The galaxy has an almost pure exponential disk-like light profile (diamonds), with a formal bulge+disk fit to the two-dimensional light distribution giving a B/D ratio of 0.04 as seen face-on. The measured disk scale length is 0.9 kiloparsecs (dot-dashed vertical line). The red line shows the Sersic profile (with $n = 0.8$) + exponential ($\mu_o = 21.2$, $\mu_e = 22.9$, $r_e = 0.30$) fit to the disk. (Here μ_o and μ_e are the central surface brightnesses for the exponential and Sersic profiles and r_e is the effective radius.) The dashed blue line shows a one-component Sersic-profile fit with $n = 1.3$. An index value of $n < 1.5$ identifies bulgeless disk galaxies in large surveys[2,3]. The galaxy would then be classified as 'bulgeless'. Images in other optical bands and the near-infrared K band give a similar fit with extremely low B/D ratios. Fits were measured using the public software GALFIT (http://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html) and a one-dimensional two-component fitting procedure, obtaining similar results. A second galaxy (DG2) shows a profile best fitted by a pure exponential, with a Sersic index of one (see Supplementary Fig. 6 and references therein). Images were created using SUNRISE[26], which creates spectral energy distributions using the ages and metallicities of each simulated star particle, and takes into account the full three-dimensional effects of dust re-processing.

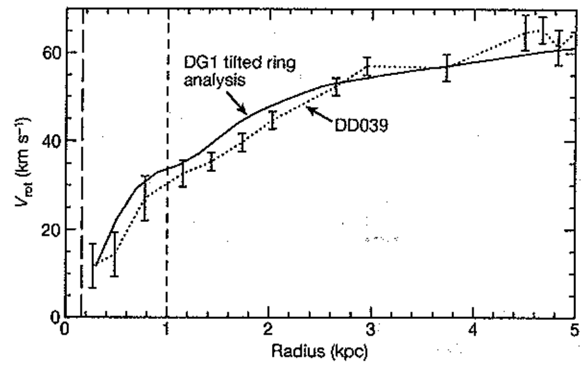

Figure 3 | The rotation curve of the simulated dwarf compared to that measured for a real galaxy. The continuous black line shows the rotation velocity of the galaxy using the actual projected velocity field and the tilted ring analysis[28] (see Supplementary Information). The dotted line shows the rotation curve of the galaxy DDO39 as measured using a similar technique[14], with standard deviation error bars. The velocity profile of both the observed and simulated galaxies imply a dark-matter distribution with a core scale length of about one kiloparsec, as directly measured in the simulation (in Supplementary Fig. 5). The long-dashed vertical line shows the force resolution of the simulation, whereas the short-dashed vertical line marks the approximate scale length of the dark-matter 'core'. The underlying dark-matter density is proportional to r^{α}, with $\alpha = -0.6$ in the central kiloparsec, consistent with observational estimates and shallower than a dark-matter-only simulation (see Supplementary Information) that would predict a steeper profile with $\alpha = -1.3$. Error bars indicate one standard deviation.

galaxies. This is a great success of our simulation; previous simulations have persistently produced rotation curves that rise rapidly in the inner regions and peak inside one scale length, symptomatic of their steep central mass distributions[5]. The dark-matter central density of DG1 has a shallow profile over a 'core' of roughly one kiloparsec in size (see Fig. 3 and Supplementary Fig. 5), comparable to those measured in many dwarf galaxies[3,13,14]. Accordingly, the dark-matter density averaged over the same radius is $10^{7.5} M_{\odot}$ kpc^{-3}, about 50% lower than in a control run in which the gas is not allowed to cool or form stars, and in which the slope of the inner dark-matter profile is instead steep, as in typical dark-matter-only simulations[6].

Outflows are the main mechanism in altering the central density profile of the baryonic component of galaxy DG1. The strongest outflows correlate with star-formation bursts, caused by mergers and strong interactions, when dense gas regions form from disk instabilities and sink to the centre owing to dynamical friction. Supernova feedback destroys these gas clumps as soon as they start forming stars. Outflows then selectively remove most low-angular-momentum gas before it is transformed into stars, effectively quenching the processes that would lead to a concentrated baryon distribution and to the formation of stellar bulges (see Supplementary Information). At present the angular momentum distribution of stars formed from the remaining gas has a median value higher than the dark matter, and lacks its low-angular-momentum tail (Fig. 4).

The removal of centrally concentrated, low-angular-momentum gas is also closely connected to the origin of shallow dark-matter profiles. As the galaxy DG1 assembles, gas starts collecting at its centre in clumps and filaments while the dark matter remains smoothly distributed. This spatial decoupling between the gas and dark matter can lead to efficient orbital energy transfer from the gas to the dark matter through gas bulk motions[8] and gas orbital energy loss. Additionally, the gas outflows ensuing from subsequent star formation rapidly remove a large fraction of the gas, leading to a significant loss of dark-matter binding energy, causing a net expansion and the formation of a shallow dark-matter profile[21,22]. Our simulations provide direct confirmation of these two mechanisms, because the expansion of the collisionless dark-matter component occurs over several gigayears, closely following the strongest outflows. Outflows happen both in smaller mass progenitors and then at the centre of the main galaxy, where the process of core formation is essentially complete by $z \approx 0.5$, when the dark-matter profile in the inner kiloparsec settles to a shallow slope with $\rho \propto r^{-0.6}$, comparable to those observed and shallower than a dark-matter-only control run, which has the canonical, much steeper profile (see Fig. 3 and Supplementary Information).

These results predict that low-mass, bulgeless disk galaxies should also have a shallow dark-matter central profile and predicts that these

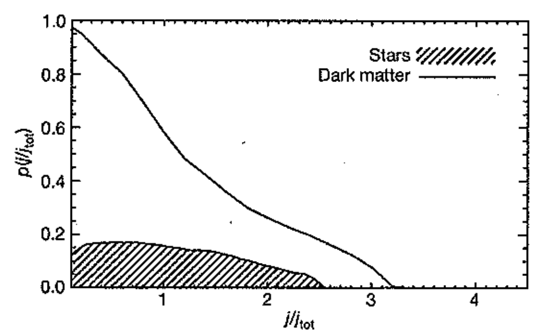

Figure 4 | A comparison between the angular momentum distribution of the stellar disk and the dark-matter halo in the simulated galaxy DG1. The panel shows the present-day time angular momentum probability distribution $p(j/j_{tot})$ (ref. 7) of disk stars (shaded area) and dark-matter particles (area below the continuous line) normalized by the average for the whole dark-matter halo ($j_{tot} = 1$). The angular momentum distribution of star particles has a narrower distribution, a higher average and significantly less low-angular-momentum material than the dark matter, owing to centrally concentrated outflows preferentially removing low-angular-momentum baryons. As a result, the radial stellar distribution is similar to that measured for normal dwarf galaxies[2,3] (see also Fig. 2).

two properties should be correlated in observed samples of nearby galaxies, given that they originate from the same physical processes.

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