

Cume 369

- (1) **10pt** The text states that “*sudden gas removal ... causes the dark matter to expand*”. How does it happen? What are the physical forces causing the dark matter to expand?
- (2) **20pt** What is the total mass of galaxy DDO39 within 5 kpc? How does it compare with the mass of the Milky Way within the same radius? Please, state your results in solar masses.
- (3) **30pt** In order to estimate the magnitude of expansion of the dark matter, let’s solve a simple problem. We assume that dm particles move on circle orbits around the center. How much do the radii of dm particles change after a half of the mass was quickly blown away by supernovae explosions? Assume that the angular momentum of each dm particle is preserved.
- (4) **15pt** “*Dense gas regions form from disk instabilities and sink to the center owing to dynamical friction*”. Please, explain why the formation of the dense lumps of gas is needed and what dynamical friction they are talking about? Is there a reason why the gas cannot get to the center of the galaxy without dynamical friction? In general, dynamical friction operates when a massive object moves through a medium and loses its energy. What forces produce the “friction”. In this particular case, what is the medium and what is the massive object?
- (5) Few questions about the standard cosmological model Λ CDM.
1. **5pt** The dark matter is believed to be composed of weakly interacting non-relativistic particles. What does “weakly interacting” mean?
 2. **5pt** In simulations the dark matter is modeled with collisionless particles. What does it mean “collisionless particles”?
 3. **5pt** What is the curvature of the Universe at present and how does it evolve with redshift? You may use the Friedmann equation provided below.
 4. **10pt** The Universe at present has about 70% of its mass in the dark energy (or cosmological constant). How big is the the dark energy contribution at the redshift of recombination? Provide a rough estimate.

The Friedmann equation for the Universe:

$$H^2 = H_0^2 \left(\frac{\Omega_m}{a^3} + \frac{\Omega_c}{a^2} + \Omega_\Lambda \right), \quad (1)$$

where $H(a)$ and H_0 are the Hubble constants at expansion parameter a and at present. Ω_m and Ω_Λ are density contributions of the matter and dark energy at present, and Ω_c is the curvature term.

Relations and constants

- Gravitational constant $G = 6.674 \times 10^{-8} \text{ cm}^3/\text{s}^2/\text{gram}$
- $1\text{pc} = 3.08 \times 10^{18} \text{ cm}$
- $M_\odot = 2 \times 10^{33} \text{ gram}$

LETTERS

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

F. Governato¹, C. Brook², L. Mayer³, A. Brooks⁴, G. Rhee⁵, J. Wadsley⁶, P. Jonsson⁷, B. Willman⁹, G. Stinson⁶, T. Quinn¹ & P. Madau⁸

For almost two decades the properties of ‘dwarf’ galaxies have challenged the cold dark matter (CDM) model of galaxy formation¹. Most observed dwarf galaxies consist of a rotating stellar disk² embedded in a massive dark-matter halo with a near-constant-density core³. 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 mergers⁷. Processes that decrease the central density of CDM halos⁸ 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 candidate⁹. Here we report hydrodynamical simulations (in a framework¹⁰ 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 Λ CDM 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 stars¹¹. 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 galaxies¹⁶. 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 cores⁸. However, such methods and the required high resolution have not been applied to cosmological hydrodynamical simulations of present-day dwarf galaxy systems ($V_{\text{rot}} \approx 60 \text{ km s}^{-1}$). 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 Λ CDM cosmology, we analyse a novel set of cosmological simulations. Baryonic processes are included, as gas cooling⁸, heating from the cosmic ultraviolet field²³, 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 regions¹⁹. 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 dwarfs²⁴ peaking at $0.25 M_\odot \text{ yr}^{-1}$ 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 $0.01 M_\odot \text{ yr}^{-1}$, 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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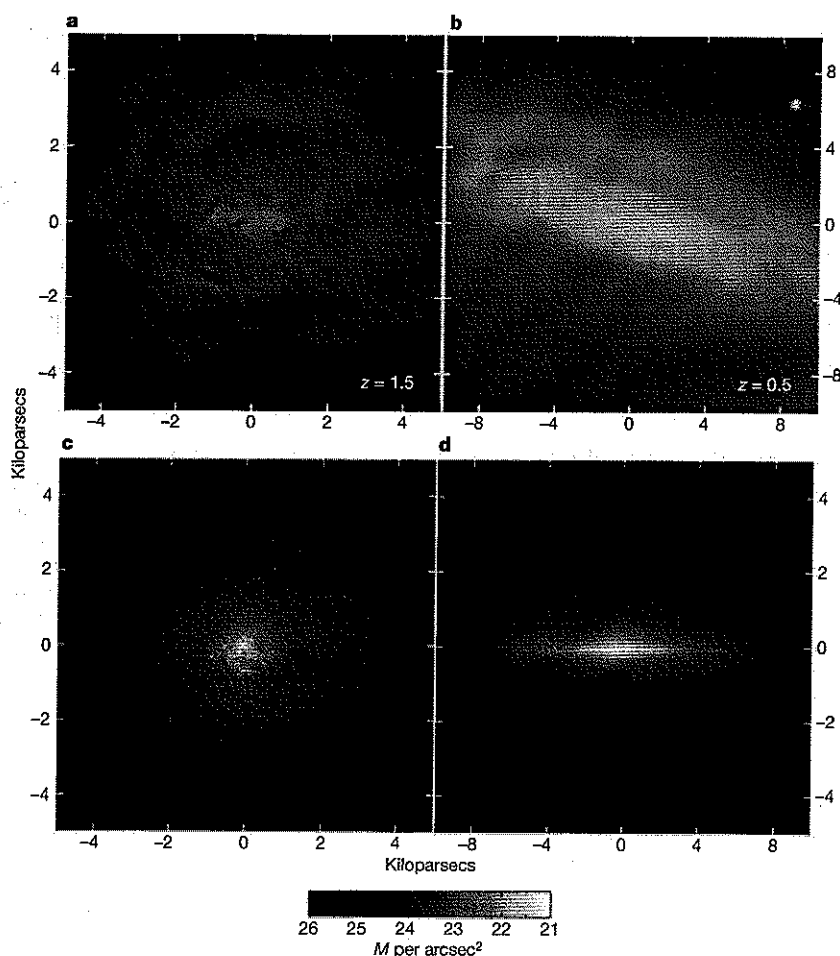


Figure 1 | The observable properties of simulated galaxy DG1. **a**, Colour-coded density map of the gas distribution at $z = 1.5$, showing the gas outflows and super shells. Distances on the axes are relative to the dark matter density maximum. **b**, The gas distribution at $z = 0.5$ when the disk 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 $M_{\text{H I}}/L_{\text{B}}$ 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 mass⁷. **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 galaxies²⁷. The rotation velocity is $\sim 55 \text{ km s}^{-1}$, 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 $10\text{--}30 \text{ km s}^{-1}$, similar to those observed in dwarfs²⁵. 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 observations¹⁷. As predicted in earlier studies²⁰, 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 images²⁶ (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”¹², that is, lacking a visible central stellar spheroid. The formation of a pure disk galaxy with structural properties typical of observed gas-rich dwarfs²⁷ 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 ($T < 10^4 \text{ K}$) 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 motions²⁸. 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

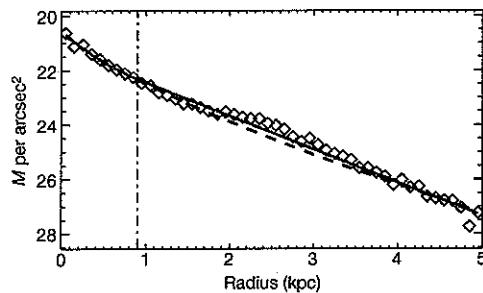


Figure 2 | The SDSS *i*-band radial light profile of the simulated dwarf galaxy DG1 at $z = 0$. Because it is less sensitive to recent star-formation events, the *i* band is often used to describe the underlying stellar mass distribution. The galaxy has an almost pure exponential disk-like light profile (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 ($\mu_0 = 21.2$, $\mu_c = 22.9$, $r_c = 0.30$) fit to the disk. (Here μ_0 and μ_c are the central surface brightnesses for the exponential and Sersic profiles and r_c 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 SUNRISE²⁶, 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.

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 distributions⁵. 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 $10^{7.5} M_\odot \text{ kpc}^{-3}$, 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 simulations⁶.

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 motions⁸ 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

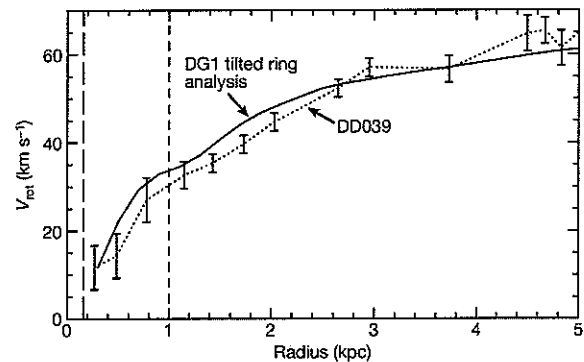


Figure 3 | The rotation curve of the simulated dwarf compared to that measured for a real galaxy. The continuous black line shows the rotation velocity of the galaxy using the actual projected velocity field and the tilted ring analysis²⁸ (see Supplementary Information). The dotted line shows the rotation curve of the galaxy DDO39 as measured using a similar technique¹⁴, 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.

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

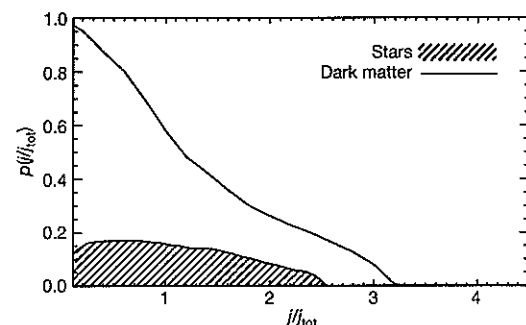


Figure 4 | A comparison between the angular momentum distribution of the stellar disk and the dark-matter halo in the simulated galaxy DG1. The panel shows the present-day time angular momentum probability distribution $p(j/j_{\text{tot}})$ (ref. 7) of disk stars (shaded area) and dark-matter particles (area below the continuous line) normalized by the average for the whole dark-matter halo ($j_{\text{tot}} = 1$). 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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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions F.G. provided the scientific leadership, designed the numerical experiments, wrote the paper and led the analysis and interpretation of the simulations. C.B. and A.B. performed part of the analysis. C.B., L.M., A.B., B.W. and P.M. helped with the interpretation and the writing of the manuscript. J.W., T.Q. and G.S. developed GASOLINE, the code used for the simulations. P.J. developed the analysis code SUNRISE. G.R. performed the kinematical analysis of the simulations.

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(1) 10pt The text states that “sudden gas removal ... causes the dark matter to expand”. How does it happen? What are the physical forces causing the dark matter to expand?

Answer: It is the force of gravity. Before the gas removal both the mass of gas and the dark matter mass were producing the force of gravity. The force of gravity decreases once the gas is blown away.

(2) 20pt What is the total mass of galaxy DDO39 within 5 kpc? How does it compare with the mass of the Milky Way within the same radius? Please, state your results in solar masses.

Answer: We can neglect random velocities at these distances and assume that the rotational velocity is equal to the circular velocity. The circular velocity is related to the mass within the radius as

$$V_{\text{circ}}^2(r) = \frac{GM(< r)}{r}. \quad (1)$$

This assumes spherical symmetry, which is a sensible assumption in this case: for realistic systems the circular velocity deviates not more than $\sim 10\%$. At 5 kpc DDO39 rotates with 60 km/s, which gives mass $M_{\text{DDO39}} = 4 \cdot 10^9 M_{\odot}$. The rotational curve of the Milky Way is already flat at 5 kpc. With the rotational velocity $V_{\text{MW}} = 220 \text{ km/s}$, we get $M_{\text{MW}} = 5.6 \cdot 10^{10} M_{\odot}$.

(3) 30pt In order to estimate the magnitude of expansion of the dark matter, let's solve a simple problem. We assume that dm particles move on circle orbits around the center. How much do the radii of dm particles change after a half of the mass was quickly blown away by supernovae explosions? Assume that the angular momentum of each dm particle is preserved.

Answer: If $V_{\text{init}}(r_{\text{init}})$ is the initial circular velocity at initial radius r_{init} , then the final circular velocity and radius are found through conservation of the angular momentum:

$$V_{\text{fin}} r_{\text{fin}} = V_{\text{init}} r_{\text{init}}. \quad (2)$$

Using $V^2(r) = GM(< r)/r$ we get:

$$M_{\text{fin}}(r_{\text{init}}) r_{\text{fin}} = M_{\text{init}}(r_{\text{init}}) r_{\text{init}}. \quad (3)$$

Mass inside each orbit decreases by factor two: $M_{\text{fin}} = 0.5 M_{\text{init}}$. This gives $r_{\text{fin}} = 2 r_{\text{init}}$. Note that the density declines dramatically: $0.5/2^3 = 1/16$.

(4) 15pt “Dense gas regions form from disk instabilities and sink to the center owing to dynamical friction”. Please, explain why the formation of the dense lumps of gas is needed and what dynamical friction they are talking about? Is there a reason why the gas cannot get to the center of the galaxy without dynamical friction? In general, dynamical friction operates when a massive object moves through a medium and loses its energy. What forces produce the “friction”. In this particular case, what is the medium and what is the massive object?

Answer: Angular momentum of the gas prevents it from falling to the center. Normal gas viscosity is very small and the only way for the to get to the center is to lose its angular momentum by interaction with the dark matter. In principle, interaction between different fragments of gas may result in redistribution of the angular momentum in gas itself. However, most of the mass in the dwarf is in dark matter. So, interaction with the dark matter likely causes the dynamical friction. In order for dynamical friction to operate, we need to have a massive and relatively compact object. In this case it will be dense clouds of gas.

(5) Few questions about the standard cosmological model Λ CDM.

1. **5pt** The dark matter is believed to be composed of weakly interacting non-relativistic particles. What does “weakly interacting” mean?

Answer: Besides the force of gravity, the only interaction between dm particles and normal matter is through the weak nuclear force.

2. **5pt** In simulations the dark matter is modeled with collisionless particles. What does it mean “collisionless particles”? *Answer: Two-body scattering can be neglected.*

3. **5pt** What is the curvature of the Universe at present and how does it evolve with redshift? You may use the Friedmann equation provided below. *Answer: In standard LCDM model the Universe has flat geometry. It stays flat during evolution. In the Friedmann equation $\Omega_c = 0$.*

4. **10pt** The Universe at present has about 70% of its mass in the dark energy (or cosmological constant). How big is the the dark energy contribution at the redshift of recombination? Provide a rough estimate.

Answer: The contribution of the Λ term is very small at the moment of recombination $z_r \approx 1100$, $a_r = 1/(1 + z_r) \approx 10^{-3} \approx 10^{-3}$. While the density of the dark energy is constant, the density of the matter scales with redshift as a^{-3} . Thus, at the moment of recombination the contribution of the Λ term is about 10^{-9} and can be neglected:

$$\Omega_{\Lambda}(a) = \frac{\rho_{\Lambda}(a)}{\rho_{\text{critical}}(a)} = \frac{\Omega_{\Lambda,0}}{\Omega_{\text{matter},0}} a^3 = 1.7 \times 10^{-9}, \quad (4)$$

where $\Omega_{\Lambda,0} = 0.7$ and $\Omega_{\text{matter},0} = 0.3$ are contributions of the Λ term and normal matter at $z = 0$.

The **Friedmann equation** describes the rate of expansion of the Universe:

$$H^2 = H_0^2 \left(\frac{\Omega_m}{a^3} + \frac{\Omega_c}{a^2} + \Omega_\Lambda \right), \quad (5)$$

where $a = 1/(1+z)$ is the expansion parameter of the Universe at redshift z . Parameters $H(a)$ and H_0 are the Hubble constants at expansion parameter a and at present. Ω_m and Ω_Λ are density contributions of the matter and dark energy at present, and Ω_c is the curvature term.

Relations and constants

- Gravitational constant $G = 6.674 \times 10^{-8} \text{ cm}^3/\text{s}^2/\text{gram}$
- $1 \text{ pc} = 3.08 \times 10^{18} \text{ cm}$
- $M_\odot = 2 \times 10^{33} \text{ gram}$

