

Baryonic Pinching of Galactic Dark Matter Halos

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High resolution cosmological N-body simulations of four galaxy-scale dark matter halos are compared to corresponding N-body/hydrodynamical simulations containing dark matter, stars and gas. The simulations without baryons share features with others described in the literature in that the dark matter density slope continuously decreases towards the center, with a density $\rho_{\text{DM}} \propto r^{-1.3 \pm 0.2}$, at about 1% of the virial radius for our Milky Way sized galaxies. The central cusps in the simulations which also contain baryons steepen significantly, to $\rho_{\text{DM}} \propto r^{-1.9 \pm 0.2}$, with an indication of the inner logarithmic slope converging. Models of adiabatic contraction of dark matter halos due to the central build-up of stellar/gaseous galaxies are examined. The simplest and most commonly used model, by Blumenthal *et al.*, is shown to overestimate the central dark matter density considerably. A modified model proposed by Gnedin *et al.* is tested and it is shown that while it is a considerable improvement it is not perfect. Moreover it is found that the contraction parameters in their model not only depend on the orbital structure of the dark-matter-only halos but also on the stellar feedback prescription which is most relevant for the baryonic distribution. Implications for dark matter annihilation at the galactic center are discussed and it is found that although our simulations show a considerable reduced halo contraction as compared to the Blumenthal *et al.* model, the fluxes from dark matter annihilation is still expected to be enhanced by at least a factor of a hundred as compared to dark-matter-only halos. Finally, it is shown that while dark-matter-only halos are typically prolate, the dark matter halos containing baryons are mildly oblate with minor-to-major axis ratios of $c/a = 0.73 \pm 0.11$, with their flattening aligned with the central baryonic disks.

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I. INTRODUCTION

There are still a multitude of open questions regarding the distribution of dark matter in galactic halos, the effect of baryons upon the structure of dark matter halos being one. Many simulations of galactic halos only take into account the dark matter (e.g. [1, 2, 3, 4, 5, 6]), but one would expect the baryonic component of the galaxy to behave very differently since it is able to cool (dissipate energy), and contract considerably. This is indeed observed in simulations containing baryons and also in nature, where the baryons form a disk and/or bulge at the center of apparently much more extended dark matter halos.

It has long been realized that this ability of baryons to sink to the center of galaxies would create an enhanced gravitational potential well within which dark matter will congregate, increasing the dark matter density there. To model this effect it is common to use adiabatic invariants or some small modification of them [7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. Such models are fre-

quently used and it is of particular interest to test the validity of these models [12, 17, 18] currently because of recent advances in mapping the velocity field of the Milky Way [19] and other galaxies. Furthermore, upcoming gamma ray experiments will look for the flux due to the self-annihilation of weakly interacting dark matter candidates from, e.g., the galactic center. Since this flux is proportional to the dark matter density squared, predictions for, and conclusions from, the data will depend strongly on the details of the effect of baryonic pinching upon dark matter halos.

In this work we aim to investigate the effects of baryons on dark matter halos in disk galaxies and test the most common models of adiabatic contraction by comparing recent cosmological N-body/hydrodynamical simulations of galaxies containing dark matter and baryons to results from N-body dark-matter-only simulations of the *same* halos. Fully cosmological simulations starting at high redshifts are used. The simulation results are known from previous studies to produce overall realistic gas and star structures for spiral galaxies [20, 21, 22], even though the numerical resolution is still far from being able to resolve any small scale features observed in real galaxies. The most important dynamical property in this paper is the creation of stable disk and bulge structures both for the gas and star components. The *angular momentum problem* is overcome by stellar feedback, implying that the

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matter is not too centrally concentrated; a generic problem of early galaxy simulations (see, e.g., [23] and references therein on forming disk galaxies in simulations). With the baryonic disks and bulges formed fully dynamically the surrounding dark matter halo response should also be realistically predicted inside the simulated spiral galaxies.

The paper is organized as follows. In section II we present the simulations, and then focus in section III, in particular, upon profile fits to the density of the dark matter halos in the simulations with and without baryons. In section IV we investigate different prescriptions which aim to predict the effects of baryons upon dark matter profiles by testing whether they are able to reproduce the dark matter profiles observed in the simulations with baryons. We then comment in section V on how these results might change the expected flux of gamma rays from dark matter annihilation in spiral galaxies, including the Milky Way. Finally, we analyze in section VI the nonsphericity of the different components of the simulations – dark matter, gas and stars – to attempt to further quantify their effects upon each other before we summarize our results in section VII.

II. SIMULATIONS

The simulated galaxies used in our work consist of two Milky Way sized galaxies with virial radii (at $z=0$) of $r_{200} \approx 200$ kpc and two smaller galaxies with virial radii of around 100 kpc. The two larger galaxies are labeled 1 and 2 and the two smaller galaxies 3 and 4; the number simply being an identifying label. Here we have followed common practice and defined r_{200} as the radius of the sphere enclosing the mass M_{200} within which the mean density is 200 times the critical density, $\rho_c = 3H_0^2/8\pi G$.

All four galaxies have been extracted from fully cosmological simulations using the HYDRA code and an improved version of the Smoothed Particle Hydrodynamics code TREESPH. Since the software generating the disk galaxies has been used in many previous works (see, e.g., [20, 21, 22]), we will only briefly mention the main features of the numerical code.

The simulations are performed in a Λ CDM cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1} = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and with the matter power spectra normalized such that the present linear root mean square (rms) amplitude of mass fluctuations inside $8h^{-1} \text{ Mpc}$ is $\sigma_8 = 1.0$. There is still some uncertainty in the accepted values of σ_8 and h , but we have tested that none of the general conclusions obtained in this paper are affected by small changes in these parameters.

The galaxies are generated by first performing a dark-matter-only simulation, using the HYDRA code, with 128^3 particles in a box of comoving length of $10 h^{-1} \text{ Mpc}$ and starting at redshift $z_i = 39$. After running this simulation, galactic size objects are identified. The simulations which include baryons (or alternatively with only

dark matter) are then set up, particles within $4r_{\text{vir}}$ at $z = 0$ are traced back to their initial conditions, the dark matter particle mass resolution is increased by up to a factor of 64, and one SPH particle, i.e. baryonic matter, per dark matter particle is added (keeping the total mass and fixing the baryonic fraction f to 0.15). The simulations are then rerun with the improved TREESPH code; incorporating star formation, stellar feedback processes, radiative cooling and heating, etc. The final result are qualitatively similar to observed disk and elliptical galaxies at $z = 0$, a result which is mainly possible by overcoming the *angular momentum problem* by an early epoch of strong, stellar energy feedback in form of SNII energy being fed back to the intrastellar medium.

To study the effect of baryons on dark matter halos in Milky Way like galaxies we use four simulated disk galaxies with the highest available resolution at our disposal. By comparing simulations with different resolutions we infer that the results are robust down to an inner radius r_{min} , which is 2 times the gravitational softening length. This is in approximate agreement also with other commonly used convergence criteria, such as $r_{\text{min}} \approx N_{200}^{-1/3} r_{200}$ (see, e.g., [6, 24] and references therein). For the larger galaxies 1 & 2 we deduce $r_{\text{min}} = 2 \text{ kpc}$ whereas for the two smaller 3 & 4 $r_{\text{min}} = 1 \text{ kpc}$. The spiral galaxies containing dark matter and baryons will be labeled with 'S' (e.g. S1) whereas those containing only dark matter will be labeled with 'DM' (e.g. DM3). There are some notable differences between the four galaxies, for example the large galaxy S1 has a very pronounced flat gas and stellar disk with a star bulge, whereas galaxy S2 is strongly barred. The gas in the two smaller galaxies has a very definite disk structure and the stars exhibit both disks and central bulges which are more centrally concentrated than the ones in the two larger galaxies.

A summary of the main parameters of the simulated galaxies is given in Table I (see [20, 21, 22] for further details).

III. DARK MATTER HALO RADIAL PROFILES

In the section on nonsphericity we will address the nonspherical aspects of the simulations in more detail, in particular the effect of the triaxiality of the dark matter halo upon the baryons and vice-versa. However before that, in order to directly compare the profiles with most others in the literature, we assume spherical symmetry and fit the galaxies with common radial profiles. One parametrization which assumes two asymptotic radial power law behaviors at both small (γ) and large (β) radii is known as the ' $\alpha\beta\gamma$ ' profile (or the Zhao profile), where the density as a function of radius is given by the expression

$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{\frac{\beta-\gamma}{\alpha}}} \quad (1)$$

TABLE I: *Main properties of dark matter halos and galaxies at $z=0$*

Simulation	S1	DM1	S2	DM2	S3	DM3	S4	DM4
Virial radius r_{200} [kpc]	209	211	200	201	100	102	98.3	97.5
Total mass M_{200} [$10^{11} M_{\odot}$]	8.9	9.3	7.8	8.0	1.0	1.1	0.93	0.91
Number of particles N_{200} [$\times 10^5$]	3.6	1.2	3.5	1.0	3.2	0.98	3.1	0.90
DM particle mass m_{dm} [$10^6 M_{\odot}$]	6.5	7.6	6.5	7.6	0.81	0.95	0.81	0.95
SPH particle mass m_{baryon} [$10^6 M_{\odot}$]	1.1	...	1.1	...	0.14	...	0.14	...
Grav. soft length DM ϵ_{dm} [kpc]	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5
Grav. soft length SPH ϵ_{baryon} [kpc]	0.6	...	0.6	...	0.3	...	0.3	...
Characteristic circular speed V_c [km/s] ^a	245	...	233	...	124	...	122	...
Specific angular momentum (bulge+disk), j_* [kpc km/s]	447	...	303	...	144	...	153	...
Specific angular momentum (cold gas), j_{cg} [kpc km/s]	1895	...	1055	...	1005	...	1093	...
Star formation rate (SFR) [M_{\odot}/yr]	1.4	...	1.7	...	0.13	...	0.15	...
$b = \text{SFR}/\langle \text{SFR} \rangle$	0.23	...	0.32	...	0.13	...	0.16	...
Baryonic disk + bulge mass [$10^{10} M_{\odot}$]	7.17	...	5.79	...	1.13	...	0.98	...
Baryonic Bulge-to-disk mass ratio	0.19	...	0.80	...	0.76	...	0.60	...

^a V_c is determined as in [20]

where α governs the radial rate at which the profile interpolates between the asymptotic powers $-\gamma$ and $-\beta$.

Often in the literature various constraints on these parameters are assumed, resulting in subclasses of less general profiles. In particular the density profile in the outer part of the galaxy halo, β , is often assumed to be 3, which is the canonical value found for halos in simulations invoking only dark matter. For this reason many authors use $(\alpha, \beta, \gamma) = (1, 3, \gamma)$ and is commonly known as the generalized Navarro, Frenk and White (NFW) profile (with the standard NFW profile having $\gamma = 1$) [1]. We in general find a significantly better fit to our profiles if we also leave α and β as free parameters. Moreover, it is obviously not certain that profiles used to characterize the halos of dark-matter-only simulations should also give good fits to the dark matter halos formed in simulations also containing baryons. We have therefore done least χ^2 fits to the profiles leaving the four parameters in Eq. (1) free (ρ_0 we always constrain by the total mass in the fitting range which we set to be between r_{min} and r_{200}). The profile fits can be seen in Fig. 1, 2 as solid lines and the parameter values are given in Table II.

It is useful to keep in mind that with four free parameters in the ' $\alpha\beta\gamma$ ' profile, there are some degeneracies in the inferred parameter values [25]. The numbers given in Table II aim to give a good parametrization of the density profiles in the fitted range, and do not necessarily claim to represent profiles that could be extrapolated into smaller radii with confidence.

We have also fitted the dark matter halo density distributions over the same radial range using exponential profiles, where the logarithmic slope changes continuously with radius as recently suggested by Navarro, Frenk and

White [2]

$$\rho(r) = \rho_{-2} \exp \left[-\frac{2}{\alpha} \left(\left(\frac{r}{r_{-2}} \right)^{\alpha} - 1 \right) \right]. \quad (2)$$

In this profile, ρ_{-2} and r_{-2} correspond to the density and radius where $\rho \propto r^{-2}$. The best fit values can be found in Table III and the profile fits can be seen in Fig. 1, 2 as dashed lines.

Finally, we have fitted single power laws to the central dark matter density profile ($r_{\text{min}} < r < 0.05r_{200}$) to determine the averaged logarithmic slope of the resolved central cusp. These slope values are found in Table IV. This can also partly be compared to the central asymptotic logarithmic slope in Eq. (1), which is $-\gamma$ (whereas in the profile in (2) the logarithmic slope is continuously decreasing towards the center).

To describe the dark matter halos we actually fit $dm/dr = 4\pi\rho r^2$ since this is representative of the actual data in the simulation. Logarithmic binning of the radius is used to minimize the effect of substructure, which becomes more important at large radii, while at the same time capturing the behavior of density profile in the central part.

In order to obtain an estimate of the variance with which to do the fits and for our subsequent analyses throughout the paper, we take five snapshots of each simulation at different times. These snapshots correspond to today's epoch and to four successive earlier times with $\Delta t = 200$ Myr, and from these we find their one standard deviation (unbiased) mean square dispersion. This Δt is long enough so that the particles in the inner regions of the simulations will have had time to completely change their positions with respect to the center of the galaxy, but a short enough timescale in total so that the overall mass profile of the halo has changed very little

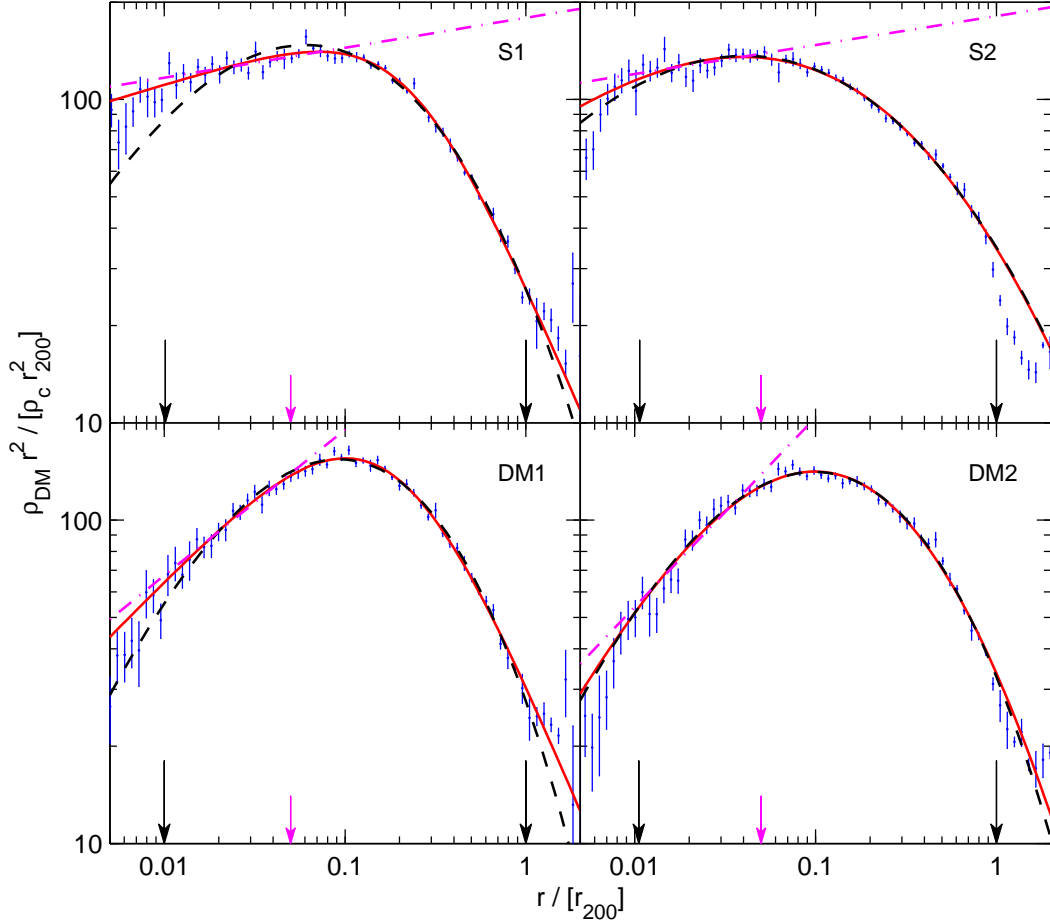


FIG. 1: *Top panels: dark matter density profiles from galaxy simulations including baryons; galaxy S1 (left) and S2 (right). Bottom panels: density profiles from halo simulations including only dark matter; halo DM1 (left) and DM2 (right). The solid, dashed and dot-dashed curves show the best fit from the parametrization given in Eq. (1), (2) and a single power law, respectively. Long arrows show the lower resolution limit (r_{\min}) and the virial radius (r_{200}), respectively. The shorter arrows indicate the upper limit for the single power law fits ($0.05 r_{200}$).*

TABLE II: *Best fit parameters for model Eq. (1) to the spherical symmetrized dark matter halos.*

Galaxy sim. with(without) baryons	$r_s[kpc]$	α	β	γ	χ^2_{dof} [46 dof]
S1 (DM1)	44.9 (36.0)	1.76 (1.47)	3.31 (3.36)	1.83 (1.42)	1.4 (1.0)
S2 (DM2)	150 (85.1)	0.486 (0.588)	4.21 (4.79)	1.49 (0.850)	1.5 (1.2)
S3 (DM3)	13.3 (14.3)	12.4 (1.387)	2.48 (2.74)	2.07 (1.70)	1.0 (2.1)
S4 (DM4)	56.1 (10.3)	2.75 (0.915)	3.48 (3.00)	2.20 (1.36)	2.1 (1.0)

(for all galaxies, the dark matter mass within 50 kpc increases by less than about 1% over the total period of 1 Gyr).

This method of estimating the variance in each bin has the effect of suppressing the influence from temporary small scale inhomogeneities in density due to dark mat-

ter subhalos (which are most common at large radii) and at the same time retaining the Poisson population variance in other bins. It turns out that the variances are approximately equal to the Poissonian values for most radial bins. This will serve as the estimate of the uncertainties in our subsequent investigations. A more detailed

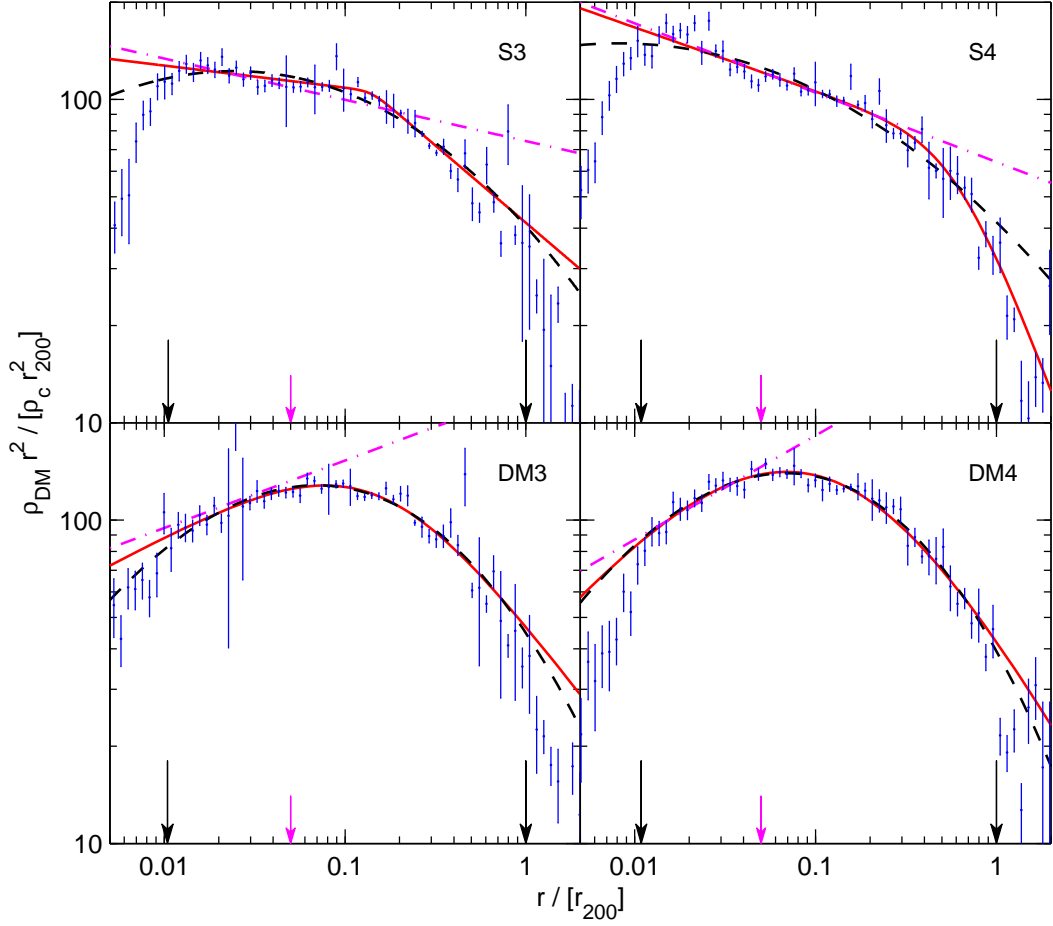


FIG. 2: *Top panels: dark matter density profiles from galaxy simulations including baryons; halo S3 (left) and S4 (right). Bottom panels: density profiles from halo simulations including only dark matter; halo DM3 (left) and DM4 (right). The solid, dashed and dot-dashed curves show the best fit from the parametrization given in Eq. (1), (2) and a single power law, respectively. Long arrows shows the lower resolution limit (r_{\min}) and the virial radius (r_{200}), respectively. The shorter arrows indicate the upper limit for the single power law fits ($0.05 r_{200}$).*

TABLE III: *Best fit parameters for model Eq. (2) to the spherical symmetrized dark matter halos.*

Galaxy sim. with(without) baryons	$r_{-2}[kpc]$	α	χ^2_{dof} [48 dof]
S1 (DM1)	11.9 (18.5)	0.185 (0.247)	3.1 (1.5)
S2 (DM2)	7.66 (18.7)	0.117 (0.226)	1.5 (1.5)
S3 (DM3)	2.30 (6.70)	0.0728 (0.132)	2.6 (2.1)
S4 (DM4)	0.750 (6.31)	0.0507 (0.153)	3.2 (0.91)

analysis of the actual uncertainties which would take into account, e.g. systematic radial dependencies from numerical and resolution effects or even effects from the implementation of physical processes themselves, is very difficult to achieve and is beyond the scope of this paper. From the five time frames no strong correlations between our bins were found and we will in practice not take into

account such eventual correlations.

Tables II-IV contain significant information: For the ' $\alpha\beta\gamma$ ' profiles one has $\rho \propto r^{-\beta}$ at large radii, and even when β is left as a free parameter, values for β around 3 emerge, albeit with a rather large scatter. Moreover, the χ^2 per degree of freedom is significantly smaller when using the ' $\alpha\beta\gamma$ ' profiles rather than the exponential profiles

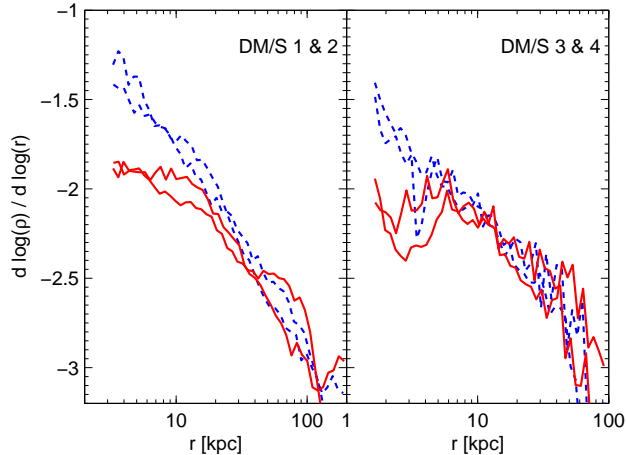


FIG. 3: Logarithmic slope of the dark matter density profiles for all halos, plotted versus radius. Solid/red curves from the simulation including baryons, and dashed/blue curves from the simulations including only dark matter. Left panel: the larger, Milky Way sized, galaxies (1 & 2). Right panel: the two smaller galaxies (3 & 4).

TABLE IV: Best fit parameters for single power law $\rho \propto r^{-\gamma}$ fits to the central dark matter density profiles ($r_{\min} < r < 0.05r_{200}$).

Galaxy sim.	γ	χ^2_{dof}
with(without) baryons		[49 dof]
S1 (DM1)	1.91 (1.56)	0.65 (1.2)
S2 (DM2)	1.91 (1.41)	0.76 (1.1)
S3 (DM3)	2.13 (1.79)	0.90 (0.92)
S4 (DM4)	2.21 (1.68)	1.6 (0.80)

for the simulation with baryons.

From the best fit parameters in Table II it follows that the asymptotic central logarithmic slope ($-\gamma$) for the dark-matter-only simulations average to -1.1 for the two larger halos DM1 and DM2 and a somewhat steeper slope of -1.5 for the two smaller galaxies. These results are, to the inner resolved radii, in agreement with other recent simulations including only dark matter (see e.g. [26] and references therein).

The effect that the presence of baryons has upon the central slope of the dark matter density profile is very pronounced, pushing the average asymptotical central logarithmic slope up to -1.7 for the larger galaxies and to -2.1 for the two smaller galaxies. Another way of seeing this systematic steepening of the profiles due to the presence of baryons is to look at the fits to the exponential profile (2) presented in Table III. For all four galaxies, the presence of baryons brings in the radius at which the density is dropping as $\rho \propto r^{-2}$ (for the smaller galaxies, this radius becomes comparable to r_{\min}).

Since all simulations have limited resolution one should

be cautious in extrapolating profiles inside the resolved radius of the simulations. To explore the inner slope further we show in Fig. 3 the logarithmic slope $d \log \rho / d \log r$. Note from this figure that there is no sign of convergence of the central slope in the simulations without baryons, whereas in the simulation including baryons the slope change is drastically less and might already have converged to a defined value. To calculate the logarithmic slope profiles without excessive particle noise we average both over the five time frames and over the five nearest radial neighbor bins (corresponding to logarithmic smearing window of 20% of our logarithmic radius range $r_{\min} < r < r_{200}$). This eliminates most of the fluctuations without biasing the slope significantly.

For the two larger galaxies Fig. 3 clearly demonstrates that the logarithmic slope is always continuously changing for the dark-matter-only simulations, while for the simulations including baryons the logarithmic slope derivative is drastically less in the central regions. This may indicate that the inner logarithmic slope converges to a value close to -1.9, i.e. close to an isothermal sphere. The picture is slightly less clear for the two smaller galaxies, but there the logarithmic slope also flattens out in the inner region to a value roughly around -2.1 (although the bin-to-bin scatter is somewhat too large to draw any firm conclusions).

If we only fit the central part of the dark matter density ($r_{\min} < r < 0.05r_{200}$) a single power law fit should work well for the simulation including baryons and we deduce from Table IV a inner logarithmic slope close to -1.9 for the two larger galaxies and an average inner slope of -2.2 for the two smaller galaxies.

Galaxy S2 is different compared to the other galaxies in several ways. For instance, for the dark-matter-only simulation of the halo (DM2), the best fit to the ' $\alpha\beta\gamma$ ' density profile yields a asymptotic central logarithmic slope of only $-\gamma = -0.85$ and a very large scale radius r_s . One thing that separate this galaxy from the others in its evolution is that it has experienced a late time merger and that there is not as strong disk structure, but rather a pronounced bar structure in the stars. Despite this the dark matter density profile is not entirely different, which seems to support the results reported in [27] – where they find that dark matter profile shapes are preserved in mergers.

The most obvious comparison with observations, concerning dynamics from dark matter, is the rotation curves. In Fig. 4 we plot the rotation curve for the gas in one of the larger galaxies (S1). The solid red line is the average in each radial bin of the magnitude of vectors $\vec{r} \times \vec{v} / |\vec{r}|$ of which there is one for each cold disk gas particle. The dashed lines correspond to the Keplerian velocities expected at each radius due to dark matter, baryons and the sum of the two.

Even though the dark matter distribution in the core of the simulation seems to asymptote to a cusp as far as it is possible to ascertain above the smallest length scale resolved, it turns out that the baryonic mass in the

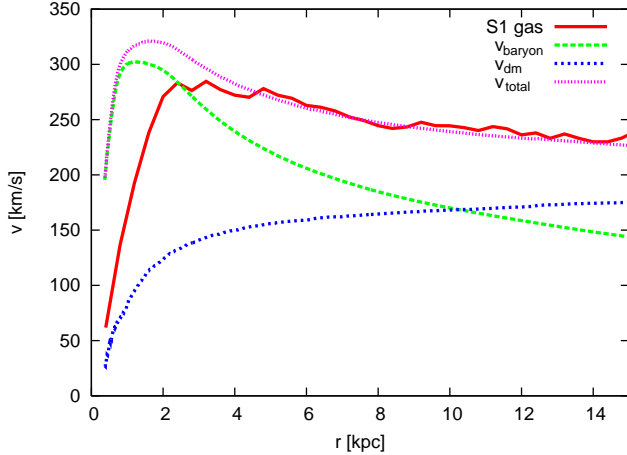


FIG. 4: Rotation curve of the disk gas for galaxy S1 (solid red curve). Also plotted are the Keplerian velocities expected due to baryons, dark matter and in total, assuming spherical symmetry ($v_x = \sqrt{GM_x(<r)/r}$).

center of the galaxy is predominantly responsible for the rotation of the inner part of the gas disk. The rotation curve is comparable to observed rotation curves of large disk galaxies [28, 29, 30].

The rotation curves in the simulations of the two smaller galaxies are somewhat too centrally peaked compared to most observations. This is probably related to the fact that these simulated galaxies don't fully overcome the *angular momentum problem* in the inner couple of kpc, and hence that the central baryonic component of these galaxies might still be somewhat too concentrated.

In the inner couple of kpc there is a discrepancy between the actual circular velocity of the gas and the total rotational velocity expected from the enclosed mass. This is mainly a numerical effect, due to gravity softening, but also partly due to effects of noncircular motions of, and pressure gradients in, the cold gas, as discussed by [31].

IV. TESTING ADIABATIC CONTRACTION

The most commonly used model of baryonic contraction was suggested by Blumenthal *et al.* [10] and is based on two assumptions, namely that the orbits of particles are circular and that the dark matter halo contracts adiabatically, i.e. slowly, compared to the dynamical time scale of the system. Consider a dark matter halo which has an initial mass profile $M_i(r)$. One can then ask what the effect would be of changing a fraction f of those particles into baryons. The dissipational baryons will cool and contract, and end up with a final mass distribution $M_b(r)$. In the adiabatic contraction model of Blumenthal *et al.*, the relationship between the initial mass profile

and the final dark matter profile $M_x(r)$ is given by

$$r[M_b(r) + M_x(r)] = r_i M_i(r_i) = r_i M_x(r)/(1-f) \quad (3)$$

which relies upon the assumption of conservation of angular momentum, a spherically symmetric gravitational potential, and the noncrossing of the circular orbits during the contraction, a criterion which gives $(1-f)M_i(r_i) = M_x(r)$.

Since this proposal was put forward, it has been established that typical orbits in N-body simulations of dark matter halos are rather elliptical (see, e.g., [32]) so that $M(r)$ changes around the orbit and $M(r)r$ is no longer an adiabatic invariant. It has therefore been pointed out by Gnedin *et al.* [12] that the relation in Eq. (3) could be modified to try to take this into account. In particular they argue that using the value of the mass within the average radius of a given orbit, \bar{r} , should give better results than that within the instantaneous radius r or the maximum radius at apogee r_a . The average radius \bar{r} for a particle is given by

$$\bar{r} = \frac{2}{T} \int_{r_p}^{r_a} \frac{r}{v_r} dr \quad (4)$$

where v_r is the radial velocity, r_p is the perihelion radius and T is the radial period. The ratio between r and \bar{r} will change throughout the halo so Gnedin *et al.* parameterize the average $\langle \bar{r} \rangle$ (\bar{r} averaged over the population of orbits at a given r) using the power law with two free parameters

$$\langle \bar{r} \rangle = r_{200} A \left(\frac{r}{r_{200}} \right)^w \quad (5)$$

For their simulations, they find values of $A = 0.85 \pm 0.05$, $w = 0.8 \pm 0.02$ (Note that their definition of the virial radius is r_{180} rather than r_{200} as used in this paper, but the effect of this difference upon A is very small; $A_{180} = A_{200}(r_{200}/r_{180})^{1-w}$.)

This power law assumption for the relationship between r and $\langle \bar{r} \rangle$ in Eq. (5) turns out to be a good model of the orbital structure of all our halos, as illustrated by, e.g., the DM1 halo in Fig. 5, where $\langle \bar{r} \rangle$ is plotted as a function of r with a power law fit running through the data. We do not actually perform the integral in Eq. (4), but rather take the average of the radii over the 5 time snapshots and bin radially, and fit to the average within each bin, to determine A and w . To calculate the (A, w) parameters a χ^2 fit is performed in 19 radial bins between r_{\min} and $0.1r_{200}$ and using the standard deviation of the average of \bar{r} in each radial bin. The results are presented in Table V.

In order to test the hypothesis of Gnedin *et al.* we first determine the best fit values of A and w directly from the orbital structure (or in other words the dark matter “ellipticity”), as discussed above. We then perform baryonic contraction of the dark matter in the simulations *without* baryons by scanning over different A and w

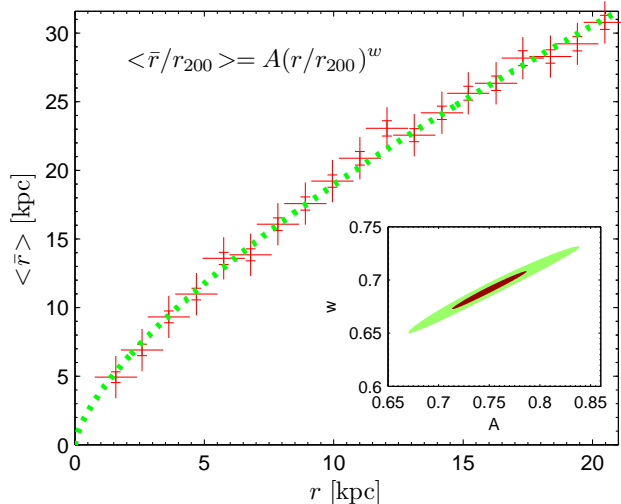


FIG. 5: Points are $\langle \bar{r} \rangle$ vs. r for the halo DM1. The best fit relation, corresponding to $(A, w) = (0.74, 0.69)$, shows that the power law assumption (5) is an excellent representation of the data. The red crosses represent the binned data and the smaller horizontal red lines represent the vertical variance on that data. The smaller figure shows in red (darker shading) the 1σ (68%) confidence region whereas the green (lighter shading) area is the 3σ (99.7%) confidence region in the (A, w) plane.

TABLE V: Values of A and w in Eq. (4) by fitting $\langle \bar{r} \rangle$ as a function of r . The ranges stated are the joint 1σ intervals.

DM halo	A_{\min}	A_{best}	A_{\max}	w_{\min}	w_{best}	w_{\max}
DM1	0.71	0.74	0.79	0.67	0.69	0.71
DM2	0.78	0.83	0.88	0.69	0.71	0.73
DM3	0.72	0.76	0.81	0.80	0.81	0.83
DM4	0.69	0.74	0.78	0.79	0.80	0.82

(see below), to test whether the values required to reconstruct the simulations *with baryons* correspond to those found directly from the orbital ellipticities.

For each galaxy, we label the halo resulting in the dark-matter-only simulation by 'DM' so that the mass inside radius r of that halo is denoted by $M^{\text{DM}}(r)$. The second simulation, including dark matter and baryons, we denote by 'S'. We thus label the mass profile of the baryons by $M_b^S(r)$, whereas the mass profile for the dark matter that will be predicted by the Gnedin *et al.* model [12] will be denoted by $M_{\text{dm}}^X(r)$. The predicted density profile $M_{\text{dm}}^X(r)$ is then compared to what is actually found from our simulation including baryons, which we denote $M_{\text{dm}}^S(r)$. To run the simulations with and without baryons with the same total mass it is necessary to have more dark matter in the simulations without baryons, a fact which we correct for using the parameter f which represents the fraction of total mass in the form of baryons. The simulations use the value $f = 0.15$ as

suggested by cosmology. The relationships between the total mass of the two simulations are thus

$$M^{\text{DM}}(r_{200}) \simeq M_{\text{dm}}^S(r_{200}) + M_b^S(r_{200}) \quad (6)$$

$$(1 - f)M^{\text{DM}}(r_{200}) \simeq M_{\text{dm}}^S(r_{200}). \quad (7)$$

The modified adiabatic contraction model is given by

$$M^{\text{DM}}(\langle \bar{r}_i \rangle) r_i = [M_{\text{dm}}^X(\langle \bar{r}_f \rangle) + M_b^S(\langle \bar{r}_f \rangle)] r_f, \quad (8)$$

and the equation for the conservation of mass given by

$$(1 - f)M^{\text{DM}}(r_i) = M_{\text{dm}}^X(r_f). \quad (9)$$

It is now possible for a given A and w (which will set the $\langle \bar{r}_i \rangle$ dependency on r_i , as well as the $\langle \bar{r}_f \rangle$ dependency on r_f) to use Eqs. (8) and (9) to find $M_{\text{dm}}^X(r)$, using only $M^{\text{DM}}(r)$ and $M_b^S(r)$, in an attempt to reproduce $M_{\text{dm}}^S(r)$. That is, we can solve the above equations numerically to find r_f . Using the above model, we can hence determine predicted pinched dark matter halo profiles for any given set of A and w values.

As discussed in the previous section, we use the rms dispersion of the number of particles in radial bins across the five time frames to estimate the uncertainties in our simulations. For each set of (A, w) values we perform the contraction of the dark-matter-only halo, and compare that with the halo from the simulation containing baryons. We restrict ourselves to the inner region of the dark matter halo where the effects of baryonic contraction are most prominent. Choosing the linear bin steps to be 1kpc (0.5kpc for the smaller galaxies) smooths out most of the random substructure density fluctuations and at the same time enables us to catch the overall shape of the density profiles. To be more precise, we do the χ^2 analysis between the inner radius r_{\min} and the outer radius $0.1r_{200}$ (i.e. 21 kpc for the two larger galaxies and 10.5 kpc for the smaller), and divide the range into 19 linear bins (consequently we have $N_{\text{dof}} = 19 - 2 = 17$ degrees of freedom (dof) in the fits).

To illustrate which (A, w) values provide good reconstructions of the baryonically compressed dark-matter-only halo profiles, we show in Fig. 6 and 7 the χ^2 of the 1σ (68% confidence) region and 3σ (99.7% confidence) region in the A - w plane. In other words inside the black/red regions, χ^2 is less than $\chi_{\min}^2 + 2.3$ and inside the gray/green regions χ^2 is less than $\chi_{\min}^2 + 11.8$. For the canonical statistical scenario, one expects a best χ^2 per degree of freedom value of around 1, which is also similar to what we find in our contour plots: $\chi_{\min}^2/N_{\text{dof}} = 0.97, 0.77, 0.64(0.51)$ and 1.3 for halo 1, 2, 3(3-s) and 4, respectively. For any reasonable variation of the number of bins and radii ranges in the inner region these confidence levels stay rather stable and the best χ^2/N_{dof} stay fairly constant.

From the contour plots it follows that the fits for $(A, w) = (1, 1)$ – which corresponds to circular orbits and therefore the original model of Blumenthal *et al.* – are significantly worse than the fits for the optimal values.

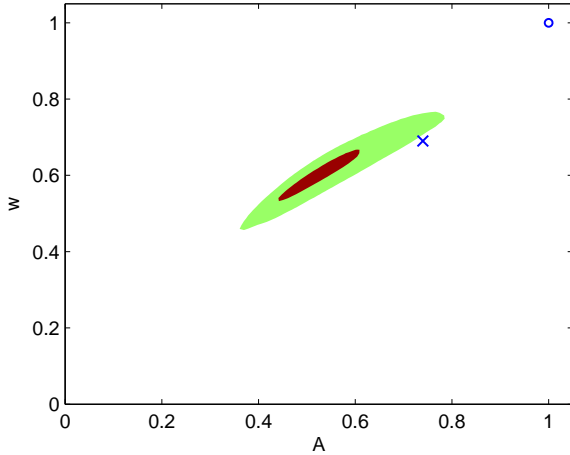


FIG. 6: Best fit parameters for reconstructing the baryonic compressed dark matter halo (S1) from its dark-matter-only halo (DM1). The red/black area is the 1σ (68%) confidence region and the green/gray is the 3σ (99.7%) confidence region. The (A, w) value, expected from the analysis of ellipticities as proposed by Gnedin et al. is marked by a cross, and the original model, by Blumenthal et al., by a circle.

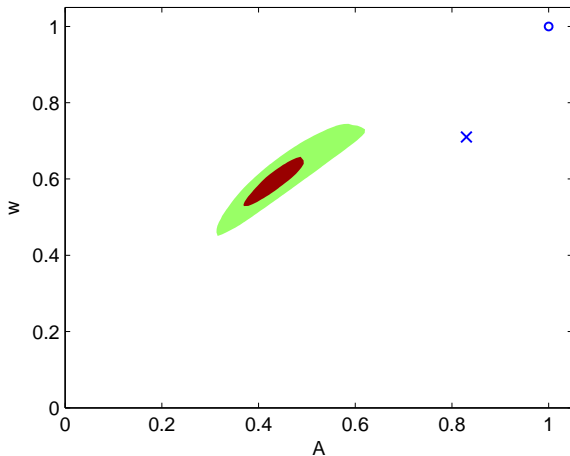


FIG. 7: Best fit parameters for reconstructing the baryon compressed dark matter halo (S2) from its dark-matter-only halo (DM2). The red/black area is the 1σ (68%) confidence region and the green/gray is the 3σ (99.7%) confidence region. The (A, w) value, expected from the analysis of ellipticities as proposed by Gnedin et al., is marked by a cross, and the original model, by Blumenthal et al., by a circle.

This can also be seen very clearly by plotting the contracted dM/dr profile using the Blumenthal *et al.* model and comparing this to the contraction observed with the best fit values. For example, for galaxy 1 the best fit value are $(A, w) \sim (0.5, 0.6)$ and the comparison are shown in Fig. 8.

The values of (A, w) obtained directly from the relation between $\langle \bar{r} \rangle$ and r in Eq. (5) are significantly different

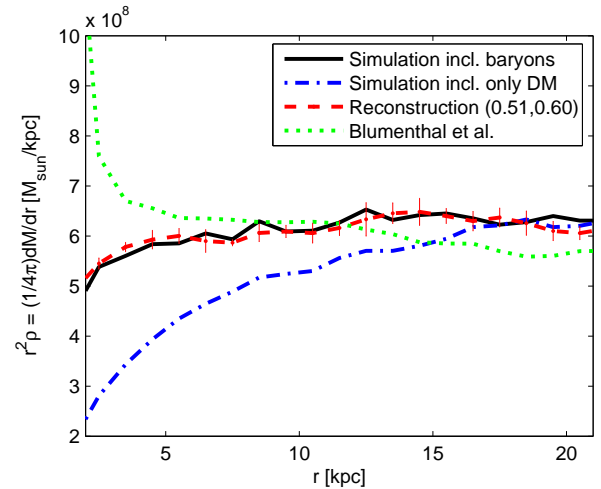


FIG. 8: Density profiles for galaxy halo S1 and DM1. The blue/dot-dashed curve is ρr^2 for the dark-matter-only simulation, and the black/solid is ρr^2 for the simulation with baryons. The green/dotted curve shows the reconstruction using the model of Blumenthal et al. (i.e. $(A, w) = (1, 1)$). The red/dotted curve with the error bars shows the best fit reconstruction, corresponding to $(A, w) = (0.51, 0.60)$.

from what is found by the above procedure. This strongly suggests (not surprisingly), that there is more physics at work than can be described by a simple two-parameter model.

From our procedure to determine the best reconstruction of the contracted dark matter halo, it should be obvious that the confidence regions in Fig. 6 and 7 should not be interpreted as strict confidence regions for some correct values of A and w . Although the 68% and 99.7% confidence levels in the figures correspond to the correct increase of χ^2 , these confidence regions should rather be thought of simply as a separation between values in the A - w plane which produce good reconstruction of the baryonic contracted halo and those which give a worse reconstruction. Moreover, there may not even be any direct physical interpretation of the A and w found this way.

We also investigated the adiabatic contraction of the two smaller galaxies 3 and 4. Again, we found that the relationship between r and $\langle \bar{r} \rangle$ in the dark matter halos of these galaxies is modeled well by the power law in Eq. (5). For these simulations the best value of (A, w) for contraction are substantially larger, and the preferred A is actually even larger than those predicted from the ellipticities. To elaborate further on this point an extra simulation of the smaller galaxy S3 was performed where stronger early stellar energy feedback was implemented at a level comparable with the top of the range considered in [20]). This extra simulation we label S3-s.

It was found that increasing the feedback strength (and therefore obtaining a less massive and somewhat more extended central galaxy) did change the best fit values of (A, w) for baryonic contraction considerably, as seen

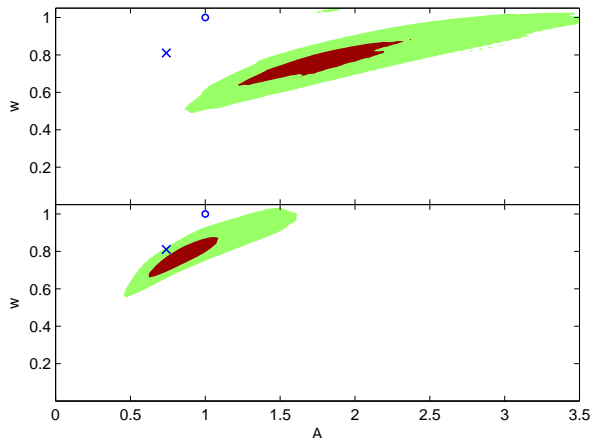


FIG. 9: Best fit parameters for reconstructing the baryon compressed dark matter halo from its dark-matter-only simulation, using two different types of stellar feedback. Upper panel is using simulation S3, whereas the lower is for an identical simulation, but with stronger stellar feedback (S3-s). The red/black area is the 1σ (68%) confidence region and the green/gray is the 3σ (99.7%) confidence region. The stronger feedback (producing a less concentrated galaxy) results in a significant change of the best fit values towards smaller A .

in Fig. 9. This suggests that the details of the feedback, and its effect upon the concentration of the baryons, is an important ingredient for predicting the relationship between the final baryonic and dark matter density profiles. Hence, we propose that it is not only the orbital structure of the dark matter halo together with the final baryonic profile which determines the final contracted profile of the dark matter halo.

Summarizing, it is found that the parametric approach with different (A, w) in Eq. (5), (8) and (9) is able to very well reproduce the pinched dark matter profiles. However, the (A, w) values are not universal, and do not in general coincide with those predicted from the ellipticity of the dark matter in Eq. (4) and (5). Moreover, the details of the stellar feedback can change which values of A and w are preferred in the modified adiabatic compression model.

V. INDIRECT DARK MATTER DETECTION

One immediate application of these results is the effect upon the expected indirect signal from dark matter in the form of weakly interacting massive particles (WIMP) annihilating in the galactic center [33]. Several authors have tried to take into account the effect of modified contraction models such as the one proposed by Gnedin *et al.* upon the expected number of annihilations from the galactic center region (see e.g. [34, 35, 36]). It is today impossible for galaxy size simulations to get anywhere near the length resolution corresponding to the very cen-

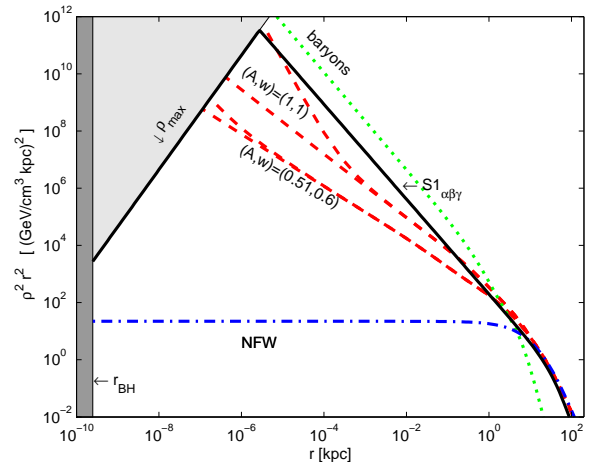


FIG. 10: Diagram showing the contraction of a standard NFW dark matter density profile (dot-dashed blue line) by a baryon profile (dotted light green line) as described in the text. The resulting dark matter profile (dashed red lines) are plotted for $(A, w) = (1, 1)$ and $(0.51, 0.6)$, each splitting into two at low radii, the denser corresponding to the density profile achieved from a baryon profile which includes a central black hole. The extrapolated density profile from Table II for the dark matter in simulation S1 is shown for comparison (solid black line). Also shown are the maximum density line and the radius corresponding to the lowest stable orbit around the central black hole.

ter of the galaxy. Nevertheless, we proceed in the spirit of comparison with the existing literature by extrapolating our results into extremely small radii.

We perform baryonic contraction of two different initial dark matter profiles with a semirealistic spiral galaxy baryon profile, taking some typical parameters from the Milky Way. To model the Milky Way baryon density we assume cylindrical symmetry, ignoring the possibility of any bar. For the central bulge of stars we assume a density of the form $\rho \propto r^{-\gamma} e^{-r/\lambda}$ while for the disk we assume a Kuzmin profile. The Kuzmin disk can be thought of as a delta function of matter in the z direction (z is the coordinate perpendicular to the disk) with a surface density $\sigma_{\text{disk}}(r) = \frac{c M_{\text{disk}\infty}}{2\pi(r^2 + c^2)^{\frac{3}{2}}}$, where $M_{\text{disk}\infty}$ is the total mass of the disk. We choose the parameters of the model to match observations of the Milky Way: $\gamma = 1.85$, $\lambda = 1 \text{ kpc}$, $c = 5 \text{ kpc}$ and with the total disk and bulge mass $M_{\text{disk}\infty} = 5 M_{\text{bulge}} = 6.5 \times 10^{10} M_{\odot}$ [37, 38, 39, 40].

The first dark matter profile we choose to contract is the standard NFW profile, i.e. $(\alpha, \beta, \gamma) = (1, 3, 1)$ with a scale radius of 20 kpc and a local density (i.e. at $r=8.0 \text{ kpc}$) of 0.3 GeV cm^{-3} .

We use the baryon profile described above to contract the dark matter profile for some of the different values of (A, w) found earlier in the paper and then calculate how the expected flux from dark matter annihilations change. The results of these contractions can be seen in Fig. 10,

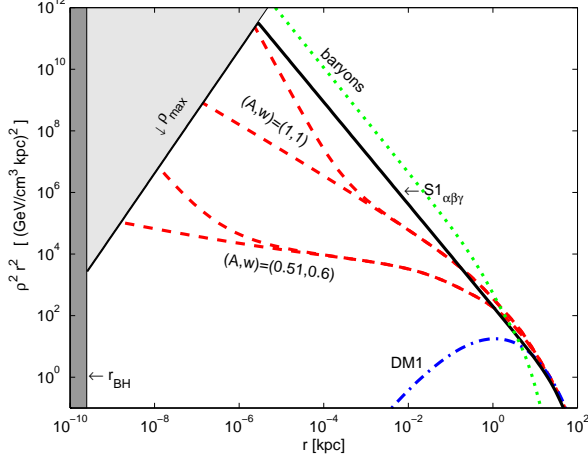


FIG. 11: The same as Fig. 10, but where the initial dark matter profile instead is the exponential profile with a continuously decreasing logarithmic slope. The initial profile parameters are from the best fit to the halo simulation DM1 as given in Table III.

which show both the result if a $2.6 \times 10^6 M_\odot$ central supermassive black hole is included in the baryonic profile and if it is not.

The same procedure is performed when the initial dark matter profile instead is an exponential profile, where the logarithmic slope is becoming continuously shallower, i.e. the profile in Eq. (2). We here use the best fit values found for the DM1 halo as given in Table III and again normalize the local density to be $\rho_l \sim 0.3 \text{ GeV cm}^{-3}$. The results are presented in Fig. 11.

We do not attempt to model the complicated dynamics at subparsec scales of the galaxy [41, 42, 43] other than trying to take into account the maximum density due to self-annihilations. In other words, a galactic dark matter halo which has survived unperturbed by mergers or collisions for a time scale τ_{gal} can not contain stable regions with densities larger than $\rho_{max} \sim m_{dm}/\langle\sigma v\rangle\tau_{gal}$. We assume $\tau_{gal} = 5 \times 10^9$ years and for the WIMP properties we adopt a dark matter mass of $m_{dm} = 1 \text{ TeV}$ and an annihilation cross section of $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$.

In Table VI we have looked at how the different values of (A,w) found in the previous section would affect the dark matter signal from the center of our idealized Milky Way. The Blumenthal *et al.* estimate gives fluxes far in excess of the other estimates. The other three sets of (A,w) in Table VI are, respectively, those typical of the best fit values found to reconstruct the larger galaxies, the best fit values obtained when reconstructing the smaller S3-s galaxy, and the best fit to the r vs $\langle\bar{r}\rangle$ curves which represent the ellipticities of the orbits in halo DM1.

All our values of (A,w) , when used to contract the dark matter halos using our analytical baryonic density profile, give large enhancements compared to the emission expected from the usual NFW profile. This is true

TABLE VI: Estimated luminosity in erg s^{-1} from dark matter annihilations in the center of contracted galaxies for different contraction parameters (A,w) from an initial NFW or the DM1 (in Table III) dark matter profile and a baryon profile including the super massive black hole, as described in the text. We quote values for the inner 10 pc and 100 pc. Note this is the total luminosity and not that in the form of some specific particle species such as photons.

A	w	NFW		DM1	
		L _{10pc}	L _{100pc}	L _{10pc}	L _{100pc}
Initial profile		3.9×10^{33}	3.9×10^{34}	2.7×10^{31}	4.7×10^{33}
1	1	2.8×10^{40}	2.8×10^{40}	9.8×10^{39}	9.8×10^{39}
0.51	0.6	2.8×10^{37}	3.5×10^{37}	7.9×10^{35}	3.5×10^{36}
0.85	0.8	5.9×10^{38}	6.0×10^{38}	2.6×10^{37}	3.3×10^{37}
0.74	0.69	6.9×10^{37}	7.8×10^{37}	1.5×10^{36}	5.0×10^{36}

even when the initial dark matter distribution follows the exponential profile as in Eq. (2) which does not initially possess a cusp. From the Table VI we deduce that the boost of the luminosity compared to the standard NFW profile takes values in the range 10^2 to 10^4 for our $(A,w)=(0.51,0.6)$ depending on the initial profile. The reader should however note that these extrapolations to very small radii neglect extra effects such as the scattering of dark matter particles on stars or a noncentralized supermassive black hole [41, 42, 43].

The total luminosity does depend upon the (A,w) value, showing that the flux which can be expected from dark matter annihilation depends upon the extra physics included in simulations containing baryonic hydrodynamics.

VI. NONSPHERICITY

In this section we relax the assumption of spherical symmetry and determine the triaxial structure of the dark matter halos, assuming ellipsoidal symmetry.

It is straightforward to obtain the moment of inertia tensor

$$I_{ij} = \sum_k (r_k^2 \delta_{ij} - r_{i,k} r_{j,k}) m_k \quad (10)$$

of the dark matter, gas or stars, by summing over the masses (m_k) and positions (r_k) of a matter component inside a spherical (or ellipsoidal) shell of a given (major) radius R . By diagonalizing I_{ij} we find both the orientation of the semiaxes and the its three eigenvalues I_i . The three principal axes (a,b,c) are then found from the relation

$$a^2 = f_R \cdot (-I_a + I_b + I_c) \quad (11)$$

and cyclic permutations thereof, where f_R is a constant the precise value of which depends upon the radial profile. To obtain an accurate result we then repeat the

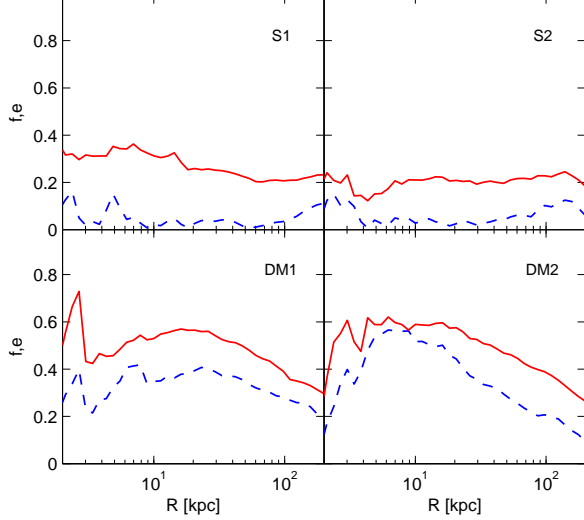


FIG. 12: The triaxial parameters $e = 1 - b/a$ (blue/dashed line) and $f = 1 - c/a$ (red/solid line) of the dark matter halos for the two larger galaxies with baryons (labeled S1 & S2) and without baryons (labeled DM1 & DM2). For a perfect oblate shape, $e = 0$ and $f > 0$ whereas for a perfect prolate shape $e = f > 0$.

search for the three axes iteratively, in each step using only particles inside an elliptical shell with semiaxes R , $(b/a)R$ and $(c/a)R$ as given by the previous step. Further iterative steps are then taken until the results converge. The principal axes are ordered such that $a \geq b \geq c$.

Having obtained the semiaxes, one determines whether a halo is prolate, in other words shaped like a rugby ball (or an American football), or oblate, i.e. flattened like a Frisbee, by introducing the parameters $e = 1 - b/a$ and $f = 1 - c/a$. If the halo is oblate or flat it means that a and b are of similar size and much larger than c and the measure $T < 0.5$ where T is defined as

$$T = \frac{a^2 - b^2}{a^2 - c^2}. \quad (12)$$

Similarly, if $T > 0.5$ then the halo is prolate.

The quantities e and f for the dark matter halos are shown in Fig. 12 and 13 (as a function of the major axis R). It is clear that the halos change from being somewhat prolate ($e \sim f > 0$) to being somewhat oblate ($e \sim 0$, $f > 0$), when baryons are included in the simulations. The values of T for the dark matter halos with and without baryons are listed in Table VII. In the presence of baryons the dark matter halo tends to form an oblate halo, whereas when there are no baryons the dark matter halo is more prolate.

Given these results, the obvious thing to check is whether the principal axes of the dark matter distributions and the baryon distributions are aligned. Figure 14 shows the alignment between the stellar disk, the gaseous

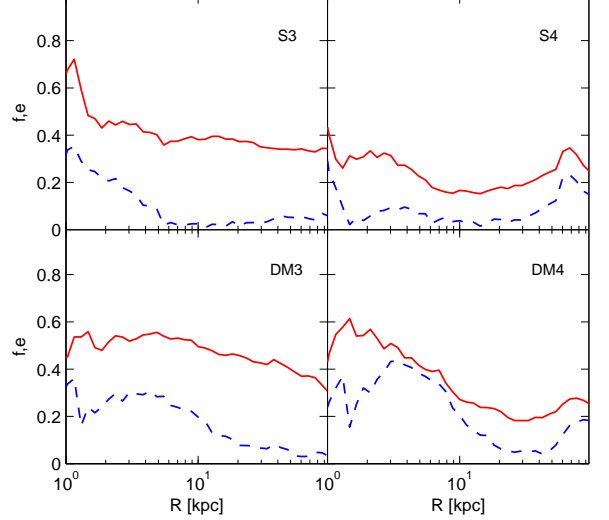


FIG. 13: The triaxial parameters $e = 1 - b/a$ (blue dashed line) and $f = 1 - c/a$ (red solid line) of the dark matter halos for the two smaller galaxies with baryons (labeled S3 & S4) and without baryons (labeled DM3 & DM4). For a perfect oblate shape, $e = 0$ and $f > 0$ whereas for a perfect prolate shape $e = f > 0$.

TABLE VII: Values of the oblate/prolate-parameter T inside 10 kpc for the halo simulations with and without baryons.

Galaxy	1	2	3	4
Sim. with baryons	0.076	0.15	0.048	0.24
Sim. without baryons	0.74	0.92	0.48	0.78

disk and the dark matter “disk”. The diagram is obtained by finding the orientation vectors of the minor axis (c) for different lengths scales (i.e. for different values of the major axis R of the ellipsoidal used in the calculation of the moment of inertia tensor I_{ij}). The parameter $\Delta\theta$ is then the angle between each of these vectors and a reference vector defined to correspond to the orientation vector of the gaseous disk determined inside $R = 10$ kpc. From the diagrams it follows that for galaxies 1, 3 and 4, the orientation of the minor axis of the gas, stars and dark matter are strongly correlated with each other. However, for galaxy 2 there is no clear alignment between the different matter components at all (not even within the gas itself at different radii). The reason for this discrepancy is likely due to that the baryonic galaxy 2 has experienced a late-time merger, making it irregular.

Figures 12, 13 and 14 provide interesting information on the interaction between baryons and dark matter in spiral galaxies. Figures 12 and 13 indicate that the formation of a disk by gas cooling and contraction causes the dark matter halo to lose most of its prolateness and instead become oblate, flattened slightly in the disk plane. Inside a few kpc, the dark matter can tend to be less

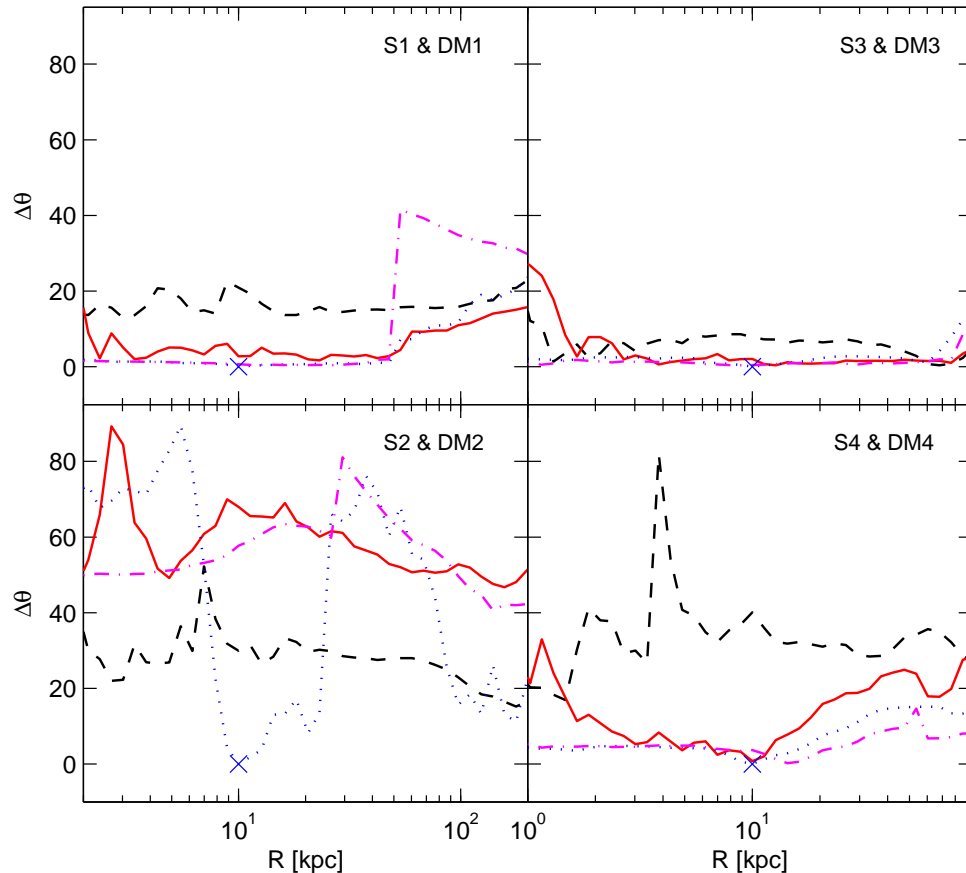


FIG. 14: Diagram showing angular alignment of the gas, stars and dark matter in our four galaxy simulations. The vertical scale is the difference in angle between the orientation of the smallest axis (around which the moment of inertia is the greatest) of the component in question relative to the axis of the gas inside 10 kpc (by definition zero and marked with a blue cross). The blue dotted line is the gas, the magenta dot-dashed line are the stars and the red solid line is the dark matter in the simulation with baryons. The black dashed line is the dark matter in the simulation without baryons, showing that the baryonic disk is aligned with the plane of the original density distribution.

oblate and instead develop a prolate structure. This is the case for, e.g., the dark matter halo in simulation S3, in which it is aligned with a strong stellar bar (see [44] for a dedicated study of central bar structures in the cold dark matter).

Additionally, Fig. 14 shows us that the orientation of the baryonic disk is rather correlated with the orientation of the flattest part of the dark matter halo in the simulation without baryons. The dark matter therefore seems to have a role in determining the orientation of the baryonic disk. Subsequently, the formation and contraction of the baryonic disk causes most of the halo triaxiality to be erased, resulting in a somewhat flattened, approximately cylindrically symmetric halo [45, 46].

The amount of triaxiality of dark matter halos is a generic prediction in the hierarchical, cold dark matter model of structure formation, and observational probes

of halo shapes are therefore a fundamental test of this model. Unfortunately, observational determination of halo shapes is a difficult task, and only coarse constraints exist. Probes of the Milky Way halo indicate that it should be rather spherical with $f \lesssim 0.2$ and that an oblate structure of $f \sim 0.2$ might be preferable (see, e.g., [47] and references therein). Milky Way sized halos formed in dissipationless simulations are usually predicted to be considerably more triaxial and prolate, although a large scatter is expected [48, 49, 50, 51, 52, 53, 54]. Including dissipational baryons into the numerical simulation, and thereby converting the halo prolateness into a slightly oblate halo, might turn out to be essential to produce good agreement with observations. In a similar numerical study [55] the effect of the baryons on the halo shape was also found to washout the triaxiality. However, in their one realization

TABLE VIII: *Best fit parameters for the ellipsoidal triaxial dark matter halo from simulation S1 (including baryons), using model Eq. (1).*

f	e	r_s [kpc]	α	β	γ	χ^2_{dof} [46 dof]
0.31	0.02	44.6	2.02	3.17	1.86	1.2

of a Milky Way size halo no clear oblateness of the galactic halo was recognized, but rather an almost spherical halo was achieved (with $f \sim e \sim 0.1$).

Having determined the ellipsoidal triaxiality of the dark matter distribution, one can include this information in the profile fits. To exemplify this, we refit the halo of S1 (the galaxy found to be most similar to the Milky Way) to the ' $\alpha\beta\gamma$ ' profile as given in Eq. (1), but now with the replacement

$$r \rightarrow \tilde{r} = \sqrt{x^2 + \frac{y^2}{(1-e)^2} + \frac{z^2}{(1-f)^2}}. \quad (13)$$

The best fit values are given in Table VIII, where we have used axis ratios as found within $R=10$ kpc (from Fig. 12 we note that we are quite insensitive to the exact choice of R).

The (α, β, γ) parameters of the ellipsoidal triaxial fit do not change much compared to the spherically symmetric fit, this is because the flattening of the dark matter halo is not very strong. However, the important difference is that the amount of flattening of the dark matter halo in the galactic plane is taken into account, and in fact, the goodness of the fit is slightly improved.

The oblate structure of the dark matter will also have some effects on the expected indirect dark matter signal [35]. However, the baryonic pinching effect does not produce such highly flattened halo profiles as the one proposed in, e.g., [56] to explain the EGRET observed diffuse gamma excess by WIMP annihilations (see also the critique in [57] on the dark matter interpretation of the EGRET signal).

VII. SUMMARY AND CONCLUSIONS

We have presented results comparing the structure of galactic dark matter halos formed in N-body simulations including only dark matter to that of *the same* halos formed in N-body/hydrodynamical simulations of galaxies, containing dark matter, stars and gas. From our selected high resolution galaxies three out of the four galaxies formed in the hydrodynamical simulations contain very distinct disks of gas and stars, and central stellar bulges, the fourth is strongly barred.

The central slope of the dark matter density profiles becomes significantly steeper when baryons are present, with the average logarithmic slope parameter

$\gamma = -d \log \rho / d \log r$ increasing from 1.3 ± 0.2 to 1.9 ± 0.2 at about 1% of the virial radius.

The pinching of dark matter halos in response to the cooling and contraction of baryons was investigated further, to test adiabatic contraction models for the case where galaxies of realistic linear sizes and other properties are formed.

In relation to the orbital structure of dark-matter-only halos, the mean of the time averaged radius $\langle \tilde{r} \rangle$ of dark matter particles versus radius r is very well described by a power law relation (specified by two parameters A and w) as suggested by Gnedin *et al.* Moreover, it is found that the Gnedin *et al.* [12] prescription for adiabatic contraction is much more successful at reproducing the density profile of dark matter in the simulations with baryons, than the standard scenario of Blumenthal *et al.* [10], in which circular orbits are assumed. However, the parameters of the Gnedin *et al.* model, (A, w) , which give the best fit for the baryonic contraction, are somewhat different from the (A, w) parameters describing the averaged orbital structure of the dark-matter-only halos. Given the (A, w) uncertainty estimates, described in the text, this difference appears to be significant. In addition, it is also found that the contraction reconstruction values of (A, w) also depend on the strength of the stellar feedback in simulations of otherwise identical halos, further indicating (perhaps as one might expect) that the effects of baryonic pinching are more complicated, than what can be captured in this two-parameter model.

Our results indicate that the amount of baryonic pinching of the dark matter halos are overestimated in earlier works applying the adiabatic compression model by Blumenthal *et al.*, at least for Milky Way sized disk galaxies. This has ramifications for predictions of the (putative) dark matter annihilation flux from the galactic center. It is found, that the flux can be reduced by several orders of magnitude, although baryonic contraction still boosts the signal significantly above the value one would expect on the basis of simulations containing only dark matter.

Finally, we have determined the triaxiality of the dark matter halos. Dark matter only halos were found to be significantly more prolate than halos containing baryons. The influence from baryons flatten the dark matter into a slightly oblate halo ($c/a = 0.73 \pm 0.11$) aligned in the same plane as the stellar/gaseous disk. Moreover, in the simulations containing baryons, galactic disks tend to form in the planes aligned with the flattest parts of the dark matter halos formed in the corresponding simulation without baryons.

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