The distribution of dark galaxies and spin bias

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ABSTRACT
In the light of the discovery of numerous (almost) dark galaxies from the ALFALFA and LITTLE THINGS surveys, we revisit the predictions of the existence of dark galaxies, based on the Toomre stability of rapidly-spinning gas disks. We have updated the predictions for ΛCDM with parameters given by the Planck18 collaboration, computing the expected number densities of dark objects, and their spin parameter and mass distributions. Comparing with the data is more challenging, but where the spins are more reliably determined, the spins are close to the threshold for disks to be stable according to the Toomre criterion, where the expected number density is highest, and reinforces the concept that there is a bias in the formation of luminous galaxies based on the spin of their parent halo.

Key words: galaxies: evolution — galaxies: formation — cosmology: theory — dark matter

1 INTRODUCTION
Star formation from the interstellar medium requires a dramatic collapse of gas, from a density ∼ 10^{-20} kg m^{-3} to ∼ 10^{3} kg m^{-3} in the case of the Sun. Such a large increase in density may be a very difficult task if the surface or volume density of gas in a disc of a galaxy is low enough, and it is not implausible that in certain situations it may be impossible to reach the density needed to form stars. Detailed physical arguments support this notion, going back to Toomre (1964), who found that a natural threshold should to keep the disk marginally unstable seem required (e.g. Krumholz & Burkert (2010); Krumholz et al. (2018)), our focus here is on the opposite case, where no stars are forming, and the criterion Q ≥ 1 is more secure and we assume that it applies. In this letter, we investigate the properties of the HI-rich gas disks discovered by Leisman et al. (2017) from the ALFALFA survey and by Butler, Obreschkow & Oh (2017) from the LITTLE THINGS survey, and look to see if they are consistent with updated predictions of gas stability, based on the Toomre Q value and the ΛCDM model.

One route to decrease the surface density of the disk is by higher values of the initial spin of the dark halo where it settles. In the hierarchical ΛCDM model of structure formation (Planck Collaboration 2018), where cold dark matter dominates the potential wells, galaxies obtain their torques because of tidal forces from the density field (Doroshkevich 1970; Heavens & Peacock 1988). For an initially gaussian field of primordial fluctuations, it is possible to predict the distribution of the halo spin parameter \( \lambda = J/E^{1/2} (GM^{5/2}) \), where \( J \) is the angular momentum of the halo and \( E \) and \( M \) its energy and mass. The result of the calculation in Jimenez et al. (1997) was that for masses below a given threshold all disk galaxies should be almost dark, i.e. the disks were Toomre stable throughout.

By the time of the prediction by Jimenez et al. (1997) there were no dark galaxies observed. Indeed, we pointed out that "A firm prediction of our model is that [dark galaxies] should be seen in deep HI surveys in voids." After more than 20 years, there has been a revolution in the coverage and sensitivity of blind HI surveys. In the same vein that we have witnessed a revolution in optical surveys, a similar trend has occurred for HI surveys. Recent HI surveys have in-
deed revealed a number of dark (or near dark) galaxies. The purpose of this short note is to update the predictions to ΛCDM, including number densities, and deriving the joint spin-mass distribution, and to analyse if the newly found HI-rich galaxies parameters are consistent with the model. Our main conclusion is that HI (almost) dark galaxies properties do indeed resemble the ones predicted, and their number density is consistent with them being the tail of the spin distribution in hierarchical tidal-torque theory as in the ΛCDM model.

2 THEORY

As in Jimenez et al. (1997), we model galaxies as disks. Assuming that the threshold for star formation is described by a Toomre stability parameter \( Q = \Sigma_c / \Sigma \), where \( \Sigma_c = \alpha \kappa_{\text{disp}} / (3.36g) \), with \( \alpha \approx 1 \), \( c_{\text{disp}} \) is the velocity dispersion of the disc and \( \kappa = 1.41(v/r)(dIn v/dln r) \), \( v \) the rotational velocity of the disc and \( r \) the distance from the centre of the disk, it is possible to compute for which masses and values of \( \lambda \) star formation will be suppressed at most radii in the disk. Taking an NFW profile (Navarro, Frenk & White 1997) for the halo, 

\[
Q(s) = \frac{\alpha}{3.36} \frac{c_{\text{disp}}^2 M_{\text{halo}}}{s \Omega M} \times \frac{\pi s}{\Omega} \frac{ds}{\delta(s)} \frac{s^{2}}{(1 + s)^2},
\]

where \( r = s r_{\text{c}} \) and the NFW scale radius \( r_{\text{c}} = r_{t}/c \), where \( r_{t} \) is the virial radius and \( c \) the concentration index\(^1\) that satisfies \( s M(s) = a^2 v^2 s M(n) \), with \( a = 2.5 \). The mass enclosed is \( M(< s) = M_{\text{c}} M(s)/M(c) \) where \( M(s) = \frac{\Gamma(1 + s) - s/(1 + s)}{\Gamma(1 + s)} \), and the virial mass within \( r_{t} \) is \( M_{\text{c}} r_{t} / \Omega_{M} \approx 200 \) is the characteristic overdensity that parametrises the central density in terms of the critical density \( \rho_{\text{crit}} \). The initial surface density is obtained from to \( s^2 - 1 - \frac{3}{2}I(s) = \sqrt{s^2 - 1} - \cos^{-1}(1/\lambda) \) for \( s \) \( > 1 \), and \( s^2 - 1 - \frac{3}{2}I(s) = -\sqrt{1 - s^2} + \ln s(1 - \sqrt{1 - s^2}) \) for \( s < 1 \). \( \Omega_{\text{m}} \) are the baryon and matter densities respectively. The velocity dispersion in the disk is taken to be \( 10 \) km s\(^{-1} \), which is the value found for galaxies with low star formation rates (Kennicutt & Evans 2012; Injamahasimanana, et al. 2012), and we fix the concentration index for the halos to be 20, characteristic of low-mass systems (Wechsler et al. 2002; White 2007). In computing the gravitational force, this formula ignores the fact that the baryons move in as the disk becomes self-supported. We modify the equation to allow the baryons which settle to the disk and move in to contribute to the gravity vector, ignoring a small correction of this sub-dominant contributor from its distribution not being spherical. This means solving \((2.5)\lambda^2 s M(s) = s^2 (1 - \beta ) M(s) + \beta M_{\text{proj}}(s) \), where \( \beta \equiv \Omega_{M} / \Omega_{\text{m}} \), and \( M_{\text{proj}}(s) \) is the total mass projected onto the disk, within scaled radius \( s \). The results for the minimum spin parameter vs mass are virtually identical.

We combine this with the lognormal distribution of halo spin parameter \( \lambda \), with mean 0.04 and dispersion 0.6 as suggested by the most recent N-body simulations (Macciò, et al. 2007; Bett, et al. 2007). The Millennium simulation finds nearly 1M halos with very high values of the spin parameter (> 0.2). The authors claim that this is partly due to the very large volume of their simulation, thus they sample the tails of the distribution more efficiently and also to the different choice of halo finder (see their Fig. 1). When they modify their halo finding algorithm they do not find such a tail of high spin halos (see their Fig. 8 and 9) but they still find spin values up to lambda 0.3. This is in better agreement with the Zurich simulations and also with recent analytic considerations that re-analyse the millennium simulation (Benson, Behrens & Lu 2020). Our derived spin values from observation are all below 0.3 except one point. The N-body simulations show that it is possible to form dark matter halos with such high spin (~ 0.3) in non-dissipative collapse. The spin parameter can be understood on the basis of tidal torque theory of density peaks (Heavens & Peacock 1988). The idea is then very simple: larger values of \( \lambda \) give rotationally-supported gas disks with larger radii and hence with lower gas surface density, and larger Toomre \( Q \) values, and hence are more likely to be stable. Given that the surface density is not constant with radius, the theory predicts that some disks will be stable in some regions but not others, but Jimenez et al. (1997) showed that disk galaxies with halo masses below about 10\(^8\) M\(_{\odot} \) should be stable throughout, in an Einstein-de Sitter Universe. Since then, the standard cosmological model has changed, and in this paper we revise the computations for a ΛCDM cosmology with a cosmological constant \( \Omega_{\Lambda} = 0.68 \), \( \Omega_{\text{m}} = 0.32 \), and \( \Omega_{b} = 0.045 \) (Planck Collaboration 2018).

3 DATA AND METHOD

Recent HI surveys have found a number of almost-dark-galaxies. These surveys have also measured in great detail the physical properties of these galaxies. For these HI-rich galaxies, the baryonic mass is dominated by the HI component (the typical ratio \( M_{\text{HI}} / M_{\text{HI}} \) is 0.03 ~ 0.1 (Leisman et al. 2017; Butler, Obreschkow & Oh 2017) while for the Milky Way the ratio is 10, so it can be as extreme as 3 orders of magnitude when compared to a normal galaxy like our own. For the very few stars that are found, the inferred star formation rates can be as low as 10\(^{-3}\) M\(_{\odot}\) yr\(^{-1}\), again 3 ~ 4 orders of magnitude below the one in the Milky Way. Clearly these are galaxies where star formation is somewhat incidental. For our analysis, we will use publicly-available data from the following surveys, which have measured physical parameters to allow comparison with the model of Jimenez et al. (1997):

(i) Leisman et al. (2017) report the discovery of 115 very low optical surface brightness, highly extended, HI-rich galaxies from the ALFALFA survey. They report very low star formation efficiencies. We will analyse the restrictive sample of 30 HI-bearing ultra-diffuse sources (R), with half light radii \( r > 1.5 \) kpc, surface brightness in the g band \( \mu_{g,R} > 24 \) mag arcsec\(^{-2} \) and absolute magnitude \( M_{g} > -16.8 \) mag. These are galaxies with baryonic components dominated by HI. We also analyse the B(road) sample with \( r_{\text{eff}} > 1.5 \) kpc, \( \mu(r_{\text{eff}}) > 24 \) mag arcsec\(^{-2} \), and \( M_{r} > -17.6 \). This B sample has higher optical surface brightness than the R one; galaxies in this sample are also more concentrated and exhibit lower halos spins than the R sample (see Fig. 2). They have higher star formation rates and are identified in GALEX, which indicates (mildly more) star formation activity than in the R sample. In any case, as they have significant HI masses, we chose to also include them in our analysis as they are also near dark galaxies.

(ii) Butler, Obreschkow & Oh (2017) report measurements of baryonic mass and specific angular momentum for 14 HI-rich rotating dwarf irregular galaxies in the LITTLE THINGS sample. These are targeted galaxies and not found in a blind survey as above, and, apart from the stability threshold, the distributions we calculate here do not directly apply.

\(^1\) In eq. 1 we correct a typographical error in eq. 2 in Jimenez et al. (1997), namely \( ds / d \Omega \) should be \( ds / d \Omega \).
Figure 1. Halo spin distribution for galaxies in different samples and from tidal-torque hierarchical collapse theory (black solid line; this distribution is normalised to unit probability). The red and blue histograms are for galaxies in the ALFALFA R and B samples respectively. The grey histogram corresponds to the LITTLE THINGS sample. The Mancera et al. sample is plotted in orange. The observed galaxies are clearly sampling the tail of the theoretical distribution.

The above samples provide us with 129 near-dark galaxies with measured values of spin that we can contrast with the predictions in Jimenez et al. (1997). The LITTLE THINGS sample has resolved imaging and thus their spin calculations are fairly robust. On the other hand, for the ALFALFA sample, only 3 galaxies have resolved observations. The rest of galaxies are point sources and thus their derived spin values are much more uncertain. This presents some difficulties in comparison, so to assess the robustness of the derived spins, we compute them in two different ways: first using the method in Leisman et al. (2017). \( \lambda = 21.8 R_d/V_{\text{rot}}^2 \), where \( R_d \) is the scale of the disk in kpc and \( V_{\text{rot}} \) the flat curve rotation value in km/s. We also estimate the dark halo spin \( \lambda \) using the HI mass as \( \lambda = 21/2 V_{\text{rot}}^2 R_d/(GM_{\text{HI}}) \), where \( M_{\text{HI}} = 5.88 \). The Planck Collaboration (2018) dark matter to baryon universal fraction. When comparing with the predictions in Jimenez et al. (1997) we keep only those galaxies for which both methods give derived spins, we compute them in two different ways: first using the method in Leisman et al. (2017). \( \lambda = 21.8 R_d/V_{\text{rot}}^2 \), where \( R_d \) is the scale of the disk in kpc and \( V_{\text{rot}} \) the flat curve rotation value in km/s. We also estimate the dark halo spin \( \lambda \) using the HI mass as \( \lambda = 21/2 V_{\text{rot}}^2 R_d/(GM_{\text{HI}}) \), where \( M_{\text{HI}} = 5.88 \). The Planck Collaboration (2018) dark matter to baryon universal fraction. When comparing with the predictions in Jimenez et al. (1997) we keep only those galaxies for which both methods give derived spins, we compute them in two different ways: first using the method in Leisman et al. (2017). \( \lambda = 21.8 R_d/V_{\text{rot}}^2 \), where \( R_d \) is the scale of the disk in kpc and \( V_{\text{rot}} \) the flat curve rotation value in km/s. We also estimate the dark halo spin \( \lambda \) using the HI mass as \( \lambda = 21/2 V_{\text{rot}}^2 R_d/(GM_{\text{HI}}) \), where \( M_{\text{HI}} = 5.88 \). The Planck Collaboration (2018) dark matter to baryon universal fraction. When comparing with the predictions in Jimenez et al. (1997) we keep only those galaxies for which both methods give derived spins, we compute them in two different ways: first using the method in Leisman et al. (2017). \( \lambda = 21.8 R_d/V_{\text{rot}}^2 \), where \( R_d \) is the scale of the disk in kpc and \( V_{\text{rot}} \) the flat curve rotation value in km/s. We also estimate the dark halo spin \( \lambda \) using the HI mass as \( \lambda = 21/2 V_{\text{rot}}^2 R_d/(GM_{\text{HI}}) \), where \( M_{\text{HI}} = 5.88 \).

4 RESULTS

The distribution of halo spins for the different samples is shown in Fig. 1 for the three different subsamples: R (red), B (blue) and LITTLETHINGS (gray). We have also plotted the theoretical distribution from tidal torque theory as a black line for mean 0.06 and sigma 0.6 for a log-normal distribution. The theoretical distribution is normalised to the peak of the observed HI galaxies. All HI samples have significant larger halo spins than the theoretical prediction, thus supporting the premise that dark galaxies represent the tail of the spin parameter distribution.

For the R sample we also display in Fig. 2 (top panel) the halo spin as a function of radius. There is a correlation between spin and radius, see Fig. 2, consistent with the idea that these disks are extended because of the high value of the halo spin. The bottom panel shows the surface brightness versus halo spin for both the R (red dots) and B sample (blue dots). The B sample has higher concentration and lower spins than the R sample. The B sample galaxies are visible in GALEX and are less dark than the R sample. They have more star formation and we expect the B sample to have potentially galaxies below the threshold for star formation.

Fig. 3 shows the distribution of spin as a function of halo mass for the R(red dots), B(blue dots) and the LITTLETHINGS samples (grey dots). For the R and B samples we have kept only those galaxies for which the \( \lambda \) values agrees to 0.05 in the two methods, as explained in § 3. The solid black line is the prediction from Jimenez et al. (1997), above which no stars are expected to form at any radius in the disk, i.e. the disk at all radii has \( Q > 1 \). The change to \( \Lambda \) domain reduces the minimum mass for galaxies to be dark. We remark that this line has no free parameters once the cosmology is chosen.

Six of the galaxies in the Leisman et al. (2017) sample have been observed by Mancera Piña, et al. (2019), who find that they are outliers in the Tully-Fisher relation, and consistent with no baryons having been ejected. We also plot these galaxies in Fig. 3.

There is good agreement with the prediction from Jimenez et al. (1997); firstly, given the uncertainties in the spin parameters, the points are consistent with being above the line. The colour density contours show the expected number of galaxies, using the appropriate survey geometry, and deriving the mass-dependent volume limits from Haynes et al. (2011) for the ALFALFA sample. The numbers shown are per 0.1 decade in dark halo mass and per 0.01
in spin value, using the baryonic mass function from Panter et al. (2007). We see that the majority of dark ALFALFA galaxies are in the high-density green region, and exist in far smaller numbers than the regular galaxies that occupy the blue regions below the line. The abundance density in the green regions is a factor ~100 lower than for star forming galaxies. The region in red is where we expect less than one galaxy in the ALFALFA survey. Note that the colouring is only relevant to ALFALFA, as the grey LITTLETHINGS sample is only relevant to ALFALFA, as the grey LITTLETHINGS sample.

### 4.1 Number density of high-spin haloes

Is the observed number of HI galaxies consistent with being the tail of the theoretical spin distribution? The HI surveys cover a volume of $8 \times 10^5 \, \text{Mpc}^3$ assuming a Planck18 cosmology (this is 1/8th of the sky for a proper distance between 25 and 120 Mpc). We use the baryonic mass function from Panter et al. (2007) with parameters for a Schechter function $\phi_\alpha = 2.2 \times 10^{-3} \, \text{Mpc}^{-3}, M_* = 1.005 \times 10^{11} \, \text{M}_\odot$ and slope $\alpha = -1.22$ and the Planck18 $\Omega_m/\Omega_k = 5.88$ ratio, the expected number of total galaxies in the above volume for the dark halo mass range $10^8 - 10^{10.2} \, \text{M}_\odot$ is $n_\text{gal} = 8 \times 10^4$ galaxies.

From the theoretical spin distribution, we expect 26 galaxies above $\lambda = 0.3$, and the surveys see 22. However, two caveats are in order: the probabilities are so low that we are extrapolating the spin distribution to higher spins than where it is reliably determined.
from simulations; and at such high spins, the NFW halo may well not be well-approximated as spherical.

We conclude that the observed number of dark galaxies in HI surveys is consistent with them being the highest spins from the theoretical distribution from hierarchical galaxy formation. It also appears that the HI surveys have found nearly all the dark galaxies in the relevant mass range, and we do not expect to find large numbers more dark galaxies above a dark halo mass of $10^{10} M_{\odot}$. There should be lower mass dark galaxies, which a lower HI flux limit should reveal\(^2\). Here our model predicts that all disks should be dark (see also Verde, Oh & Jimenez (2002)). For dark halo masses above $3 \times 10^{10} M_{\odot}$ we predict that there should be dark galaxies only above $\lambda > 0.25$, which are extreme values for the spin halo. There should be $10^{-8}$ Mpc\(^{-3}\) of these, so a larger volume than the current ALFALFA volume is needed to have a good chance of finding one of these.

5 SUMMARY

We have compared the observed properties of the almost-dark galaxies, recently found in local HI surveys, to the predictions of the model proposed in Jimenez et al. (1997). In this model we proposed that disk galaxies with high spin would be dark as they would be Toomre stable. This led us to predict a population of dark galaxies. Here we have updated our predictions to the CDM cosmology and compared to the spins, masses and number densities of the observed dark galaxies. While all the HI-rich galaxies do contain some stars, these are highly subdominant to the baryonic mass budget of the galaxies (< 10%). Furthermore, their star formation rates are also 3 – 4 orders of magnitude below that of the Milky Way (which is itself not a very vigorous star forming disk). Therefore, while acknowledging that the theory is not a perfect description, omitting for example star formation activity that might arise from a small central bulge, we compare the observed almost-dark galaxies with disks that the theory indicates should be completely stable.

We have shown that the mass and spin distribution of the observed dark galaxies is in agreement with our prediction. Although measuring the spin parameter for unresolved galaxies is challenging, they appear to inhabit the region that is Toomre stable, and moreover preferentially the part of this region that has the highest expected number density. The colours and surface brightness of dark galaxies are also consistent with predictions. We have also shown that the number density of the HI dark galaxies is consistent with them being the tail of the spin parameter distribution predicted from hierarchical tidal torque theory. The predicted and observed abundance agree, so we predict that significant numbers of new dark galaxies would only be found at lower masses (in fainter HI samples) or in small number at higher masses (up to $3 \times 10^{10} M_{\odot}$), and extremely high spin; see green region in Fig. 3). This would be consistent with what is inferred from weak lensing surveys regarding the abundance of low mass galaxies (Jimenez, Verde & Kitching 2018) in the cosmological volume.

The HI near-dark galaxies, as well as the three dark galaxies in (Janowiecki et al. 2015), are all chosen to be located in isolated environments with over-densities nearby. This is in line with the predictions of tidal-torque theory that high-spin halos will be in the low-density regions. Berta et al. (2008) find an anti-correlation between halo mass and spin in SDSS galaxies which is not seen in the dark galaxies, and find lower spin values than the HI samples, as expected. Our findings imply that there is a spin bias in galaxy formation similar to the peak bias in Kaiser (1984) but here arising from the spin parameter of the halo influencing the stability of the disk to star formation.

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DATA AVAILABILITY

The data underlying this article are available in the article and references therein.

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