Stellar feedback sets the universal acceleration scale in galaxies

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ABSTRACT
It has been established for decades that rotation curves deviate from the Newtonian gravity expectation given baryons alone below a characteristic acceleration scale \( g_\text{crit} \sim 10^{-8} \text{cm s}^{-2} \), a scale promoted to a new fundamental constant in MOND-type theories. In recent years, theoretical and observational studies have shown that the star formation efficiency (SFE) of dense gas scales with surface density, SFE \( \sim \Sigma/\Sigma_{\text{crit}} \), with \( \Sigma_{\text{crit}} \sim (p/m_\star)/(\pi^2 G) \sim 1000 \text{M}_\odot \text{pc}^{-2} \) (where \( p/m_\star \) is the momentum flux output by stellar feedback per unit stellar mass formed). We show that the star formation efficiency, more correctly, scales with the gravitational acceleration, i.e. that SFE \( \sim g/\Sigma_{\text{crit}} \equiv (G M_{\text{enc}}/R^2)/(\pi p/m_\star) \), where \( M_{\text{enc}}(< r) \) is the total gravitating mass and \( g_{\text{crit}} \equiv (\rho/m_\star)/\pi = \pi G \Sigma_{\text{crit}} \sim 10^{-8} \text{cm s}^{-2} \approx g_\text{crit} \). It follows that the characteristic galactic acceleration \( g_1 \) corresponds to the acceleration scale above which SF is ‘efficient’ (and outflows ‘inefficient’), and so baryons inevitably dominate the mass. This also explains the “deep MOND” scaling \( g_{\text{obs}} \sim (g_{\text{baryon}} g_1)^{1/2} \) (where \( g_{\text{baryon}} \) is the acceleration due to baryons alone) apparent at low accelerations. We further show that \( g_1 \) can be expressed in terms of fundamental constants (gravitational constant, proton mass, and Thomson cross-section): \( g_1 \sim 0.1 G m_p/\sigma_T \).

Key words: galaxies: formation – galaxies: evolution – cosmology: dark matter

1 INTRODUCTION
The kinematics of galaxies require something beyond the Newtonian gravity of baryonic matter (e.g., Rubin et al. 1978, 1980; Bosma 1981a,b), an amazing observation that has moved from controversial to iron-clad over the past five decades (e.g., Bershady et al. 2011). In conjunction with observations of the cosmic microwave background and large-scale structure of the Universe (e.g., Planck Collaboration et al. 2018), this observation has led to the commonly-accepted idea that the mass content of the Universe is dominated by dark matter. In the standard \( \Lambda \) cold dark matter (ΛCDM) cosmology, dark matter reconciles observations with the fact that, according to general relativity, Newtonian gravity should be valid throughout the Universe whenever gravitational fields are weak (i.e., not in the immediate vicinity of compact objects such as black holes).

It is nevertheless curious within this model that the effects of dark matter appear not at a characteristic radius within galaxies, nor at a characteristic total mass, but rather at a critical acceleration scale. For gravitational accelerations \( g \gg g_1 \approx 1.2 \times 10^{-8} \text{cm s}^{-2} \), baryons dominate the gravitational dynamics of galaxies, while for \( g \ll g_1 \), dark matter dominates. This observation led Milgrom (1983a,b,c) to propose that modifying Newton’s law of gravity (or inertia) in the regime of very small accelerations, rather than the introduction of dark matter, is the correct interpretation of galaxy dynamics. More recently, Lelli et al. (2017) have shown that the total gravitational acceleration in disk galaxies is approximately predicted by the acceleration provided by the baryons alone, with the acceleration scale \( g_1 \) providing the transition point above which the observed acceleration is given solely by that of the baryons and below which some additional acceleration is required.

Several groups have argued that this “Radial Acceleration Relation” (RAR) is a natural outcome of ΛCDM simulations (Keller & Wadsley 2017; Navarro et al. 2017; Ludlow et al. 2017; Dutton et al. 2019), but it is not immediately obvious why. In the context of ΛCDM, it is clear that something must connect the baryonic content of a disk galaxy

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Figure 1. Ratio of the young stellar mass formed to the expelled gas mass in GMCs predicted by different theoretical models as a function of total mass surface density $\Sigma_{\text{tot}}$, which is equivalent to an effective acceleration $g_{\text{eff}} \equiv \pi G \Sigma_{\text{tot}}$ plotted on top in units of $g_\ast$ (the observed characteristic acceleration scale of galaxies). The dashed line shows the simple analytic scaling from Eq. 2 for comparison. All the models predict that $M_\ast,\text{young}/M_{\text{gas,expelled}} \to 1$ as $\Sigma_{\text{tot}}$ exceeds $\Sigma_{\text{crit}} \sim 10^3 M_\odot$ pc$^2$, i.e. star formation becomes efficient. These results come primarily from (magneto)hydrodynamic simulations (Colín et al. 2013; Geen et al. 2017; Gavagnin et al. 2017; Grudić et al. 2018; Kim et al. 2018; Grudić et al. 2019), and all include stellar feedback at least in the form of radiation from massive stars. The Murray et al. (2010) results are based on semi-analytic calculations. Error bars denote the full range of results obtained in studies that survey only one value of $\Sigma_{\text{tot}}$ and vary either cloud mass or physical prescriptions.

2 PHYSICAL MODEL

2.1 Scaling of the Star Formation Efficiency

The scaling of the star formation efficiency as a competition between gravity and stellar feedback has been extensively studied over the last few decades, both in the context of individual star-forming clouds and for entire galaxies (e.g. Larson 1974; Rees & Ostriker 1977; Dekel & Silk 1986; Silk 1997; Efstathiou 2000; Murray et al. 2005, 2010; Fall et al. 2010). Below we sketch a simplified derivation that captures the core of one’s present understanding of self-regulated star formation.

Consider a “patch” of gas in a galactic disk (or cloud) of mass $M_{\text{gas,initial}}$ and area $A \sim \pi R^2$ which is Jeans unstable and begins to cool and form stars. These stars will act back on the collapsing gas, injecting momentum at a rate per unit area $dP_{\text{kin}}/dA$ which is proportional to the mass of young stars (since the feedback is dominated by massive stars), $dP_{\text{kin}}/dA \sim (\dot{m}_* A)/M_\ast,\text{young}/A$ (where $\dot{m}_*$ is the momentum injection rate per stellar mass formed). If this exceeds the force per unit area on the gas from gravity $\sim \pi G M_{\text{tot}} M_{\text{gas}}/R^2 = \pi G M_{\text{gas,initial}}\Sigma_{\text{tot}}$, then the weight of the gas column is unbound, i.e. SF ceases and gas is ejected when

$$M_\ast,\text{young}/M_{\text{gas,expelled}} \sim \frac{\pi G M_{\text{tot}}}{(\dot{m}_*/A)} \frac{\Sigma_{\text{tot}}}{\Sigma_{\text{crit}}}$$

where $\Sigma_{\text{tot}} \equiv M_{\text{gas}}/A$ and $\Sigma_{\text{crit}} \equiv (\dot{m}_*/A)(\pi^2 G)$.

In the last few years, a considerable body of work has explored the SFE and demonstrated that such a scaling, with a roughly constant $\Sigma_{\text{crit}} \sim 1000 M_\odot$ pc$^{-2}$, works remarkably well at describing both observations (e.g., Wong et al. 2019) and detailed numerical simulations of cloud collapse (e.g., Hopkins et al. 2012; Colín et al. 2013; Raskutti et al. 2016; Hopkins et al. 2018; Hopkins & Grudić 2018; Kim et al. 2018; Li et al. 2019). We compile in Figure 1 SFE predictions for GMCs from various simulations that include stellar feedback. The compilation shows that there is an emerging consensus that the SFE scales linearly with $\Sigma_{\text{tot}}$ over at least two orders of magnitude in surface density, reaching $\sim 1$ for $\Sigma_{\text{tot}} \gtrsim \Sigma_{\text{crit}}$.1 Although the model predictions vary at the factor $\sim 2 - 3$ level at fixed $\Sigma_{\text{tot}}$, much of the scatter can be attributed to differences in initial conditions, definitions, and numerical methods (e.g., Hopkins & Grudić 2018; Geen et al. 2018; Grudić & Hopkins 2019).

Moreover, the ensemble and time-averaged version of this simple scaling can explain the observed Schmidt-Kennicutt relation in terms of $\dot{m}_*/A$ (or its time-integrated equivalent $\langle \dot{m}_* A \rangle$; e.g., Silk 1997; Thompson et al. 2005; Ostriker & Shetty 2011; Hopkins et al. 2011; Faucher-Giguère et al. 2013; Semenov et al. 2016; Orr et al. 2018). Taken one step further, this also naturally leads to the scalings for momentum-conserving galactic outflows (e.g., Murray et al. 2005; Hopkins et al. 2012; Hayward & Hopkins 2017), with the same constant $\langle \dot{m}_* A \rangle$ appearing.2

The value $\langle \dot{m}_* A \rangle$ thus plays a critical and “universal” role in star formation. It is important to note that

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1 It is common in the star formation literature to define the SFE as $M_\ast,\text{young}/(M_{\text{gas,expelled}} + M_\ast,\text{young})$, effectively neglecting the possibility of a significant dark matter component.

2 If instead of the non-equilibrium derivation of Eq. (1), one considers a time-steady galactic SFR $M_\ast$, and wind mass loss $M_{\text{tot}}$ with momentum flux $M_{\text{tot}} v_{\text{escape}} \sim (\dot{m}_*/A) M_\ast A \sim (\dot{m}_*/A) M_\ast,\text{young}$ (where $\dot{m}_* A = \int \langle \dot{m}_* A \rangle dt = \langle \dot{m}_* A \rangle t_*$ for a single stellar population), one obtains the usual momentum-driven wind scaling $M_{\text{tot}} \sim 1/v_{\text{escape}}$ (e.g., Murray et al. 2005; Davé et al. 2011) and we can write $M_\ast/(M_{\text{gas,expelled}} - (M_\ast)/A - v_{\text{escape}}/\langle \dot{m}_* A \rangle \sim (t_* \Omega)^{-1} (g_{\ast}/g_{\crit})$, where $t_* \Omega^{-1} \sim 1$ is a correction applicable when $\Omega^{-1} \gtrsim t_*$. 

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the value of \( \langle p/m_\ast \rangle \) is similar regardless of whether photo-heating, radiation pressure, stellar OB winds, or supernovae (SNe) dominate the feedback, as they all provide similar momentum injection rates for standard stellar population models (e.g., Leitherer et al. 1999; Bruzual & Charlot 2003; Agertz et al. 2013; Hopkins et al. 2011). For example, radiative feedback provides \( \langle p/m_\ast \rangle \sim c^{-1} (L/M)_\ast \sim c^{-1} (1000 L_\odot/M_\odot) \sim 1000 \text{ km s}^{-1}/40 \text{ Myr} \) while SNe, which release their momentum over a stellar evolution timescale \( t_\ast \sim 40 \text{ Myr} \), also output \( \langle p/m_\ast \rangle \approx 1000 \text{ km s}^{-1}/40 \text{ Myr} \), nearly independent of ambient medium properties (e.g., Martizzi et al. 2015; Kim & Ostriker 2015).

For these reasons, although controversy and unsolved questions still remain in the study of star formation and details of e.g. Eq. 1, this controversy has largely centered on the exact order-unity coefficients (e.g. fraction of the momentum coupled vs. “vented,” corrections for turbulent media, and non-linear time-dependent effects), and question of which feedback mechanisms dominate on which spatial and timescales (none of which alters the dimensional scaling in Eq. 1).

2.2 A Characteristic Acceleration Scale from Stellar Feedback

For historical reasons, the convention in the star formation literature has been to express Eq. 1 in terms of a critical surface density and it is common to assume (e.g., in the context of individual molecular clouds) that \( \Sigma_{\text{tot}} \) is dominated by baryons. However, the derivation in the previous section shows that the relevant quantity is actually the total gravitational acceleration from all matter, \( g_{\text{tot}} = G M_{\text{tot}}/r^2 \). Noting this, Eq. 1 can be rewritten as

\[
M_{\ast \text{, young}}/M_{\text{gas, expelled}} \sim \frac{\pi G M_{\text{tot}}}{\langle p/m_\ast \rangle R^2} = \frac{g_{\text{tot}}}{g_{\text{crit}}}
\]

(2)

\[
g_{\text{crit}} \equiv \frac{1}{\pi} \langle p/m_\ast \rangle \sim \pi G \Sigma_{\text{crit}} \sim 2 \times 10^{-9} \text{ cm s}^{-2} \sim g_\ast.
\]

Expressed in cgs units, we see that \( g_{\text{crit}} \sim 0.3 \langle p/m_\ast \rangle \) corresponds numerically to the “universal” acceleration \( g_\ast \) of galaxies.

Consider now what happens in different limits of the gravitational acceleration, as implied by Eq. 2 and illustrated in Figure 2. If \( g_{\text{tot}} \ll g_{\text{crit}} \), then \( M_{\ast \text{, young}}/M_{\text{gas, expelled}} \ll 1 \) and the fraction of the total gas mass converted to stars is small. Thus, if dark matter initially dominates \( M_{\text{tot}}(< R) \), it will generally continue to do so. In the opposite limit, where \( g_{\text{tot}} \gg g_{\text{crit}} \), the SFE is high and baryons cannot escape the galaxy. In such an instance, where feedback is ineffective, dissipative gas accretion within dark matter halos is easily sufficient to allow baryonic matter to dominate over dark matter (Fall & Efstathiou 1980; Katz et al. 1996). As a result, \( g_{\text{crit}} \sim g_\ast \) will demarcate the transition between the baryon-dominated and dark-matter-dominated regions of a galaxy.

Figure 2. Illustration of the two opposite limiting behaviours of a star-forming patch of gas localized within a radius \( R \) within a galaxy, as determined by the acceleration (or equivalently, mass surface density) scale according to the physical arguments in §2.1. If \( \Sigma_{\text{tot}} \approx M(< R)/\pi R^2 \ll \Sigma_{\text{crit}} \) (or equivalently, \( g_{\text{tot}}(R) < g_\ast \)), star formation will be inefficient, most gas mass will be ejected, and dark matter will continue to dominate where it did before. If \( \Sigma_{\text{tot}} \gg \Sigma_{\text{crit}} \) (or equivalently, \( g_{\text{tot}}(R) \gg g_\ast \)), star formation will be efficient, and baryonic matter will eventually dominate. As a result, \( g_\ast \) demarcates the transition from baryon- to dark-matter-dominated regions.
In the previous section we argued that, at large accelerations \( g_{\text{tot}} \gg g_1 \), the total mass is expected to be dominated by baryons and therefore

\[
M_{\text{tot}} \approx G M_{\text{bar}}(< r)/r^2 \approx \frac{g_{\text{baryon}}}{G} M_{\text{baryon}}(< r)/r^2 \quad \text{(where \( M_{\text{baryon}}(< r) \) is the baryonic mass enclosed in \( r \)), as is indeed observed.}
\]

We now consider in more detail the low-acceleration (“deep MOND”) regime, \( g_{\text{tot}} < g_1 \).

In this regime (corresponding to large galacto-centric distances in normal galaxies, and all radii in many dwarf and low-surface brightness galaxies), the accelerations are observed to scale approximately as \( g_{\text{tot}} \approx (g_{\text{baryon}} g_1)^{1/2} \) (e.g., Lelli et al. 2017). Equivalently (since \( g_{\text{tot}} \approx V_c^2/r \) in terms of the circular velocity \( V_c \)),

\[
V_c = (GM_{\text{baryon}}(< r) g_1)^{1/4} \quad \text{i.e. rotation curves are asymptotically “flat” (\( V_c \to \text{constant as} \ r \to \infty \) with a universal scale \( g_1 \) above which \( g_{\text{tot}} \approx g_{\text{baryon}} \).
\]

This classic result, which is generally interpreted as evidence for dark matter, was a key motivation for introducing MOND; rather than assuming Newtonian gravity with \( g_{\text{tot}} = g_{\text{Newtonian}} = GM_{\text{tot}}/r^2 \) at \( g_{\text{tot}} < g_1 \) (requiring \( M_{\text{tot}} \gg M_{\text{bar}} \), i.e. dark matter), Milgrom (1983a) proposed \( M_{\text{tot}} = M_{\text{bar}} \), but with a modified acceleration law \( g_{\text{tot}} \to \text{MOND} \approx (g_{\text{Newtonian}} g_1)^{1/2} = (g_1 GM_{\text{baryon}}(< r)/r^2)^{1/2} \) when \( g_{\text{tot}} < g_1 \).

But in the limit \( g_{\text{tot}} \ll g_1 \), our Eq. 2 implies that the stellar mass \( M_{\ast} \sim \langle g_{\text{tot}}/g_1 \rangle M_{\text{gas,initial}} \approx \langle g_{\text{tot}}/g_1 \rangle f_0^0 M_{\text{tot}} \), where \( f_0 = M_{\text{gas,initial}}/M_{\text{tot}} = \text{the initial “total” supply of baryons.} \)

Solving for the total mass,

\[
M_{\text{tot}}(< r) \approx \frac{g_{\text{crit}}}{g_{\text{tot}}} M_{\ast}(< r) \approx \frac{g_{\text{crit}}}{g_{\text{tot}}} \left( \frac{1 - f_0}{f_0^0} \right) M_{\text{baryon}}(< r),
\]

where \( f_0 = M_{\text{gas}}/M_{\text{gas,initial}} + M_{\ast} \) is the gas fraction determined by the “relic” gas mass \( M_{\text{gas,initial}} \) that remains after expulsion by stellar feedback. Using the above relations, standard Newtonian dynamics imply that the total acceleration \( g_{\text{tot}} = g_{\text{Newtonian}} g_1 \) is:

\[
g_{\text{tot}} \approx \frac{G M_{\text{tot}}(< r)}{r^2} \approx \frac{g_{\text{crit}}}{g_{\text{tot}}} \left( \frac{1 - f_0}{f_0^0} \right) \frac{G M_{\text{bar}}(< r)}{r^2} \approx \frac{g_{\text{crit}}}{g_{\text{tot}}} g_{\text{baryon}} \quad \text{(4)}
\]

\[
\Rightarrow g_{\text{tot}} \approx \left( g_{\text{baryon}} g_{\text{crit}} \right)^{1/2},
\]

where \( g_{\text{crit}} = g_{\text{crit}} (1 - f_0)/f_0^0 \) only differs from \( g_{\text{crit}} \) at the order unity level. Identifying \( g_{\text{crit}} = g_{\text{tot}} \), this is exactly the scaling observed.

Thus, not only the characteristic acceleration \( g_1 \), but also the asymptotic scalings at both low and high accelerations that define the observed RAR (and MOND, by construction) emerge naturally. Equivalently, the fact that observed rotation curves are approximately flat at large radii does not require a “conspiracy” or “coincidence” between baryons and dark matter: rather, stellar feedback ensures the baryons self-regulate with the scaling needed to ensure approximately flat \( V_c \).\(^4\) In modern parlance, Eq. 2 predicts a stellar mass-halo mass relation at low masses of \( M_{\ast} \sim (g_{\text{tot}}/g_{\text{crit}}) M_{\text{gas,initial}} \approx M_{\text{tot}}^2 \) (since \( g_{\text{tot}} \) and \( M_{\text{gas,initial}} \approx M_{\text{tot}} \)) while \( g_{\text{crit}} \) is constant), in good agreement with the relation observed and needed to reproduce both the galaxy luminosity functions and the baryonic Tully-Fisher relation (e.g., McGaugh et al. 2000; Mozer et al. 2010; Behroozi et al. 2013). This in turn leads automatically to the observed RAR (Wheeler et al. 2018).

\[L_{\text{Edd, i}} = \frac{4 \pi G M_{\text{pc}}}{c^2}, \quad \text{(6)}\]

where \( M_i \) is the mass of an individual massive star and \( c \) is the Thomson cross-section. So \( L_{\text{Edd, i}} \) \( \propto (L/M)_{\ast} \), where the \( f_{\text{massive}} \) is the mass fraction in massive stars: to reproduce the more accurate full stellar population calculation for a standard IMF (Leitherer et al. 1999), \( f_{\text{massive}} \sim 0.03 \).\(^5\) Thus we have \( (p/m)_i \sim f_{\text{massive}} (4 \pi G m_p)/c^2 \). Putting these together, we obtain:

\[
g_1 \sim (4 f_{\text{massive}}) \frac{G m_p}{c^2} \sim 0.1 \frac{G m_p}{c^2} - 0.5 \frac{G m_p}{c^2} \left( \frac{m_e}{m_p} \right)^2, \quad \text{(7)}
\]

where the last expression uses \( c \) \( \approx \frac{4 \pi G m_e}{(c^2)} \), in terms of the fine-structure constant \( \alpha \), the Planck constant \( h = h/2 \pi \), the electron mass \( m_e \), and the speed of light \( c \).

\[3 \text{ DISCUSSION} \]

\[3.1 \text{ Departures from universality} \]

Recent observational analyses have cast serious doubt upon a fundamental RAR to which all galaxies must conform exactly (Rodrigues et al. 2018; Stone & Courteau 2019; Chang & Zhou 2019), contrary to previous claims that the observed scatter is fully consistent with measurement error. Hence, whatever the origin of \( g_1 \), it is likely emergent rather than fundamental in nature. This fits with the picture presented in this paper: although \( g_{\text{crit}} \) sets a characteristic scale, there is no reason why galaxies should conform **exactly** to a single RAR. For example, galaxy formation is the product of both in-situ star formation and hierarchical merging (e.g., radii (though for e.g. a galaxy in a Navarro et al. 1996b dark matter halo it varies extremely weakly with radius): this reflects the fact that rotation curves are not perfectly flat (e.g., Salucci & Burkert 2000; Courteau & Dutton 2015).

\^[3\] Since the SFE is low in this regime, the expelled gas mass is close to the total initial gas mass.

\^[4\] We note the factor \((1 - f_0)/f_0^0\) is not exactly constant at large

\^[5\] Krumholz (2011) argue that the form of the IMF, and by extension \( f_{\text{massive}} \), are also expressible in terms of fundamental constants.

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Anglés-Alcázar et al. 2017), with merging becoming increasingly important at higher masses, e.g. for massive elliptical galaxies. Feedback from active galactic nuclei (AGN), rather than stars, is also expected to be most important in massive galaxies. Interestingly, while lower-mass disk galaxies prefer the characteristic acceleration described here, the massive elliptical do not (though they do preserve "memory" of the mass profiles of merged galaxies; see Boylan-Kolchin et al. 2005). Thus, effects like variations in galaxy assembly history and AGN feedback might drive scatter in the RAR and rotation curve shapes.

### 3.2 Effect of IMF variations

Another source of scatter would be variations in the stellar IMF: \( \rho/\mu_{\text{m}} \) is sensitive to the massive stellar content of a stellar population, so within a given galaxy the observed \( g_{\text{c}} \) should vary with it accordingly. Random variations in \( f_{\text{massive}} \) are present in any stellar population "sampled" from an IMF due to the finite number of stars, but in particular the effect of "incomplete" sampling of the IMF upon \( \rho/\mu_{\text{m}} \) becomes pronounced for stellar populations less massive than \( 10^8 \, M_{\odot} \) (Murray & Rahman 2010; Kim et al. 2016). We thus expect increased scatter in the BTFR and RAR in ultra-faint dwarf (UFD) galaxies with \( M_* < 10^8 M_{\odot} \).

It is also possible for the IMF to vary systematically from one galaxy to another, and \( g_{\text{c}} \) with it. However, the factor \( f_{\text{massive}} \) is fairly well-constrained in an average sense: if it varied strongly with galaxy or local environmental properties, the slopes and normalizations of the Schmidt-Kennicutt and \( M_* - M_{\text{halo}} \) relations would be quite different. Furthermore, direct observations are consistent with an IMF that is common to all galaxies (Bastian et al. 2010; Offner et al. 2014). Therefore, while variations in the measured \( g_{\text{c}} \) could conceivably be driven by IMF variations, it seems likely that they would be dominated by other sources of variations, such as galactic environment and assembly history. Insofar as the IMF is roughly universal across cosmic time and feedback does not depend strongly on factors such as metallicity, the arguments presented above imply that (1) the characteristic acceleration scale should not vary systematically with redshift and (2) the observation that \( g_{\text{c}} \approx c H_0 \) in the low-redshift Universe (Milgrom 1983a) is a numerical coincidence.

### 3.3 Additional Details in Cosmological Calculations

In \( \Lambda \)CDM, dark-matter-only simulations predict NFW-like dark matter profiles with \( \rho \propto r^{-1} \) on small scales. In such halos, the maximum (central) acceleration is nearly constant, \( g_{\text{c}} \approx 3 \times 10^{-9} \, \text{cm} \, \text{s}^{-2} \) (or central \( g_{\text{DM}} \approx 100 \, M_{\odot} \, \text{pc} \, \text{c}^{-2} < \Sigma_{\text{crit}} \)), with very weak dependence on halo mass and/or redshift, although the presence of baryons and stellar feedback can strongly alter this (e.g. Navarro et al. 1996a; Governato et al. 2010; O’norbe et al. 2015). A "pure" dark halo therefore has \( g_{\text{tot}} \lesssim g_{\text{crit}} \) at all radii.\(^6\) But if all of the available baryons fall in, conservation of specific angular momentum implies circularization in a disk with extent \( r \approx \lambda R_{\text{vir}} \) (where \( R_{\text{vir}} \) is the virial radius; e.g., Fall & Éfstathiou 1980; Mo et al. 1998).

The acceleration in the galaxy \( g_{\text{tot}} \approx 2 \times 10^{-8} \, (1 + z)^2 \, \text{cm} \, \text{s}^{-2} \) (\( \Sigma_{\text{bar}} \approx 500 \, (1 + z)^2 \, M_{\odot} \, \text{pc}^{-2} \)) then approaches the critical value. There are therefore several ways that halo centers can become strongly baryon-dominated: (a) most of the baryons fall in by \( z = 0 \), (b) a smaller fraction of baryons fall in at high redshift, or (c) the baryons lose angular momentum and more efficiently sink to the center.

Properly accounting for the complexities of galaxy formation requires much more detailed modeling. But of course, this is what cosmological simulations and semi-analytic models do. These calculations have indeed shown that the characteristic acceleration scale \( g_{\text{c}} \), and more detailed scaling relations such as the RAR and baryonic Tully-Fisher relation (BTFR), emerge naturally in \( \Lambda \)CDM provided the models accurately treat stellar feedback (e.g. Navarro et al. 2017; Ludlow et al. 2017; Keller & Wadsley 2017; Dutton et al. 2019). More specifically, previous studies have shown that in \( \Lambda \)CDM models that produce the "correct" galaxy sizes and masses, the characteristic \( g_{\text{c}} \) appears in rotation curves as observed; Wheeler et al. (2018) showed more explicitly that as long as galaxies are broadly consistent with the observed BTFR, this is essentially guaranteed. And it is well known that stellar feedback with \( (\rho/\mu_{\text{m}}) \) similar to the values assumed here, based on standard stellar evolution models, is necessary to reproduce these scaling relations in \( \Lambda \)CDM (e.g., Somerville & Davé 2015). The simple arguments presented in this paper do not supplant these much more detailed and sophisticated calculations. Rather, they help demonstrate that the observed universal acceleration scale of galaxies does not require a "conspiracy" between many different fine-tuned components nor a modified theory of gravity: stellar feedback explicitly contains an acceleration scale that maps directly to the acceleration scale seen in galaxy scaling relations.

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\(^6\) This alone can explain, in part, why systems with \( g_{\text{tot}} \gg g_{\text{c}} \) must be baryon-dominated, but it does not explain why systems with \( g_{\text{tot}} < g_{\text{c}} \) could not also be baryon-dominated.
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