Model for Gravitational Interaction between Dark Matter and Baryons

Federico Piazza[1,2] and Christian Marinoni[3]
[1]*Dipartimento di Fisica, Università di Milano Bicocca, Piazza delle Scienze 3, I-20126 Milan, Italy*
[2]*Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 2EG, United Kingdom*
[3]*Laboratoire d'Astrophysique de Marseille, Traverse du Siphon, BP 8, 13376 Marseille, France*
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We propose a phenomenological model where the gravitational interaction between dark matter and baryons is suppressed on small, subgalactic scales. We describe the gravitational force by adding a Yukawa contribution to the standard Newtonian potential and show that this interaction scheme is effectively suggested by the available observations of the inner rotation curves of small mass galaxies. Besides helping in interpreting the cuspy profile of dark matter halos observed in *N*-body simulations, this potential regulates the quantity of baryons within halos of different masses.

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Lacking evidence of direct detection, the presence, nature, and quantity of dark matter (DM) must be, in general, inferred from the kinematic and distribution properties of baryons. A model based on the growth of small fluctuations through gravitational instability in a universe dominated by cold dark matter (CDM) provides a satisfactory fit to a wide range of properties of visible structures on scales $\gtrsim 1\ h^{-1}$ Mpc [1]. Recently, however, some apparent inconsistencies in relating DM and baryon properties on subgalactic scales have been highlighted, prompting the investigation of radical models to explain the discrepancy.

Low surface brightness (LSB) galaxies are dominated by dark matter [2] whose distribution can be traced by the rotation properties of a dynamically unimportant stellar component. Therefore, these galaxies provide the best laboratories where to test the consistency of the CDM scenario. Recent high-resolution studies of the inner ($\lesssim 5$ kpc) rotation curves of LSB galaxies suggest that the dark matter is distributed in spherical halos with nearly constant density cores ($\lesssim 1$ kpc) [3–5]. These observations seem to collide with the predictions of CDM models which produce halos with compact density cusps and steep, universal mass-density profiles $\rho \sim r^{-\beta}$ with $\beta \sim 1$–1.5 (e.g., [6,7]). This disagreement must now be taken seriously since it is not easily interpreted in terms of observational uncertainties [8] or artificial resolution effects in the CDM simulations [9].

A parallel problem is that hierarchical clustering theories with scale-invariant primordial perturbations show significantly more virialized objects of dwarf-galaxy mass in a typical galactic halo than are observed around the Milky Way [10]. Possible solutions to this conflict range from nonstandard models of inflation [11] or models in which the Universe is dominated by warm, self-interacting or annihilating DM (e.g., [12]) to hydrodynamical mechanisms that prevent accreting baryons to cool into stars (e.g., [13]).

In the absence of an obvious astrophysical mechanism, the purpose of this Letter is to investigate if the various mismatches between observations and CDM predictions, which, however, appear to be characterized by a common physical length at subgalactic scales, reflect a more fundamental theoretical problem concerning the nature of the gravitational attraction between exotic (dark) and standard (visible) matter.

Occasionally, modifications of gravity have been proposed on scales larger than those investigated here in order to describe the flatness of the rotation curves without the need of dark matter [14] (see [15] for a review). The picture that we propose, on the contrary, aims to modify neither the successful DM paradigm nor the standard baryonic physics at any scale length. We speculate that, in the Newtonian limit of approximation (small curvatures and small velocities in Planck units), the gravitational interaction in the *mixed*, dark-visible sector (i.e., that between baryonic and nonbaryonic particles) is dampened on small ($\sim$ kpc) scales.

We parametrize a general small-scale modification of gravity in the mixed sector, by adding to the standard $1/r$ potential a Yukawa contribution which is active only between visible and dark matter particles. This choice is motivated by the known short-range character of the Yukawa interaction and by its simple analytical properties in both position and momentum space.

Accordingly, we rewrite the total gravitational potential acting on the baryons as $\phi = \phi_N + \alpha\,\phi_Y$, where ϕ_N is the usual Newtonian potential,

$$\nabla^2 \phi_N = 4\pi G(\rho_D + \rho_B), \tag{1}$$

and where, weighted by the strength parameter α, ϕ_Y is the Yukawa contribution:

$$(\nabla^2 - \lambda^{-2})\phi_Y = 4\pi G \rho_D. \tag{2}$$

The parameter λ is the typical length scale above which ϕ_Y dies out exponentially. Note that the Yukawa contribution to the total gravitational potential "felt" by baryons is sourced by the DM energy density ρ_D only.

By inverting Eq. (2) the familiar exponential behavior of the Yukawa potential is recovered. Neglecting the contribution of the baryons in Eq. (1), the gravitational potential $\phi(\mathbf{x})$ felt by a visible test particle in the presence of a distribution of DM $\rho_D(\mathbf{x}')$ amounts to

$$\phi(\mathbf{x}) = -G \int d^3x' \rho_D(\mathbf{x}') \frac{1 + \alpha e^{-|\mathbf{x}-\mathbf{x}'|/\lambda}}{|\mathbf{x} - \mathbf{x}'|}. \qquad (3)$$

For the critical value $\alpha = -1$ the gravitational attraction between two point particles of different species does not diverge and is maximally suppressed in the small distance limit. We have tested our hypothesis of gravitational suppression by fitting the parameters of this Yukawa model using the rotation curves of LSB galaxies.

We perform the integration (3) in the case of a spherically symmetric distribution of DM, and we find that the contribution of a spherical shell of radius r' and thickness dr' to the Yukawa part of the potential is given by

$$\frac{d\phi_Y(r)}{2\pi G} = -\frac{\lambda}{r}(e^{-|r-r'|/\lambda} - e^{-(r+r')/\lambda}) r' \rho_D(r') dr'.$$

Note that since the Gauss theorem does not hold for ϕ_Y [see Eq. (2)] a spherical shell at r' generally does contribute to the net force at some internal point $r < r'$.

A general prediction of CDM models is that dark matter halos should have a steep central cusp; i.e., their density profiles have pure *power-law forms*. By introducing a rescaled dimensionless radius $x \equiv r/\lambda$, we thus focus on a density profile of the type $\rho_D(x) = \rho_0 x^{-\beta}$. In this relevant case the integral (3) can be solved analytically in terms of confluent hypergeometric functions of the first kind $\Phi(\alpha; b; z)$. The velocity curve, $v^2 = r|d\phi/dr|$, is given by

$$\frac{v^2(x)}{4\pi G \rho_0 \lambda^2} = \frac{x^{2-\beta}}{3-\beta} + \frac{\alpha}{2(2-\beta)}[F(x, \beta) + F(-x, \beta)], \qquad (4)$$

where

$$F(x, \beta) = \left(1 - \frac{1}{x}\right)[|x|^{2-\beta}\Phi(1; 3-\beta; x) - \Gamma(3-\beta)e^x].$$

At large radii ($x \gg 1$, $r \gg \lambda$), the velocity curve (4) flattens down to the standard Newtonian behavior, $v \propto x^{(2-\beta)/2}$. In the inner regions, however, the Yukawa contribution is efficient and the curve may be approximated by a different power law; in this case the Newtonian exponent for the velocity gets a correction that we have estimated as $-\alpha[1 + \beta(1-\alpha)]/11$. In the case of a Navarro-Frenk-White (NFW)[7] inner profile ($\beta = 1$), Eq. (4) reduces to

$$\frac{v^2(x)}{4\pi G \rho_0 \lambda^2} = \frac{x}{2} + \frac{\alpha}{x}[1 - e^{-x}(1+x)], \qquad (\beta = 1).$$

We have investigated the consistency and the universality of this gravitational paradigm, by fixing the model parameters by means of the observed (but theoretically unexplained) kinematics of low surface brightness galaxies. To this purpose we have used high spatial resolution H_α rotation curves measured and reduced by different authors [4,5,16,17] according to independent observational strategies and techniques (see Fig. 1).

We have assumed that the LSB halo is the dominant mass component, and we have not attempted to model and remove the contribution from the galactic disk to the rotation, which is taken to be negligible (*minimal disk* hypothesis; i.e., the mass-to-light (M/L) ratio of the material in the disk is $M/L \sim 0$, e.g., [17]). Our results may be described as follows:

(a) The parameter α is remarkably stable for all the objects considered. Moreover, its mean value $\alpha = -1 \pm 0.1$ physically suggests that, independently of the phenomenologically adopted Yukawa model, the effective force between baryons and DM tends to *vanish* on scales smaller than some characteristic length λ.

(b) The best fitting value for β (1.35 ± 0.05), the inner slope of the halo mass-density universal profile, is in excellent agreement with the CDM calculations by [7,9]. In other terms, the observed kinematics of visible matter in dwarf galaxies is dynamically induced by the dark matter clumps predicted by numerical simulations. As is well known, a pure Newtonian potential fails to reconcile observations with theoretical expectations. For example, observations would suggest bimodal DM profiles, i.e., deviations from the predicted single power-law

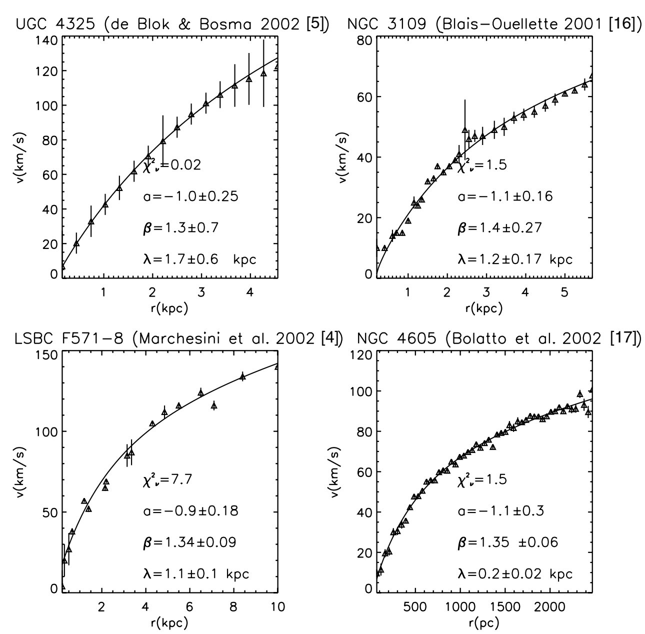

FIG. 1. Velocity models derived by fitting the high resolution rotation curves of LSBC F571-8 [4], NGC 4325 [5], NGC 3109 [16], and NGC 4605 [17] with Eq. (5). The fit is performed assuming no dynamical contribution from the disk (minimal disk hypothesis). The best fitting parameters for each galaxy are shown in the corresponding panel. Error bars represent 1σ uncertainties.

distribution in the core of the DM clumps (e.g., [8,18]). Even assuming that there are at least two distinct mass components (halo and disk) that are contributing to the Newtonian gravitational potential [17], a single power-law model may be recovered but at the cost of a significantly flatter slope ($\beta \sim 0.6$) than predicted by simulations.

(c) The scale below which our proposed modification of the Newtonian DM-baryon interaction becomes effective is less robustly constrained. While the data of [4,5,16] seem to point, consistently, to a value $\lambda = 1.1 \pm 0.08$ kpc (assuming $H_0 = 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$), the rotation curve of NGC4605 [17] favors a smaller value ($\lambda \sim 0.2 \pm 0.02$ kpc). Future velocity surveys of the inner regions of local dwarf galaxies will help in better constraining the range of variation of this fundamental length and in understanding if, as we assume here, NGC 4605 may be considered as nonrepresentative of the general kinematics of dwarf galaxies. Finally, we note that above this kiloparsec scale, in the external halo regions, a standard Newtonian regime is recovered, and a NFW density well describes the observed flattening of the rotation curves.

We have also investigated how this proposed universal form for the coupling of the DM and baryons may help in interpreting some CDM results. Many authors (e.g., [19]) have argued that in order to match CDM models with observations, some mechanism must prevent a large number of dwarf galaxies from forming in low mass halos. Much attention has been focused on investigating astrophysical and hydrodynamical mechanisms that may suppress the efficiency of converting baryons into stars in small galactic systems (e.g., [20]): in particular, supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy (e.g., [21], but see [22]) and photoionization effects that prevent baryons to cool into stars (e.g., [23]).

In our picture, the lack of a significant luminous component in small halos may be interpreted noting that, in addition to local, baryonic *physical* processes, a *cosmological* mechanism contributes to regulate the quantity of baryons that falls into halos of different masses. The growing of the baryonic density contrast $\delta_B = \delta\rho_B/\bar{\rho}_B$ after decoupling is described in linear perturbation theory, neglecting radiation effects [24,25], by the equation

$$\ddot{\delta}_B + 2H\dot{\delta}_B = \nabla^2\delta\phi, \qquad (5)$$

where a dot means differentiation with respect to the proper time t, $H = \dot{a}/a$ is the hubble parameter, and $\delta\phi$ is the perturbation of the gravitational potential. DM perturbations, approximately the only gravity sources, grow almost independently $\delta_D \equiv \delta\rho_D/\bar{\rho}_D \simeq (a/a_{dec})\delta_D^{dec}$ and create the potential wells where baryons fall in. In the standard scenario $\nabla^2\delta\phi \simeq 4\pi G\,\delta\rho_D$, and the right-hand side (rhs) term of (5) very efficiently drives the growth of baryonic perturbations of any length scale (the fraction $\delta_B/\delta_D \simeq 1 - a_{dec}/a$, in fact, becomes of order unity already at redshift, say, $z = 100$). By using (1) and (2), on the contrary, the driving term on the rhs of (5) becomes scale dependent: $\nabla^2\delta\phi = 4\pi G(1 - \lambda^2\nabla^2)^{-1}\delta\rho_D$. We can gain some insight by noting that, as long as the proper size a/k of a perturbation keeps small in units of $\lambda \sim$ kpc, this source can be approximated as

$$\nabla^2\delta\phi \approx 4\pi G\frac{(a/k)^2}{\lambda^2}\delta\rho_D.$$

A galaxy of mass $10^9 M_\odot$, for instance, grew out from perturbations of length $\sim 10^{-1}$ kpc at decoupling; in this case the relative driving term on the rhs of (5) is initially suppressed by a factor $\sim 10^{-2}$. This dampening is of order $\sim 10^{-4}$ for galaxies of $10^6 M_\odot$. The full solution of (5) in our gravitational scenario is plotted in the upper panel of Fig. 2 in terms of the fraction δ_B/δ_D and for different masses.

Using this result, it is straightforward to compute the baryon fraction $f = (\rho_B/\rho_D)$ inside shells reaching the turnaround. In doing this we use a $n = 1$ power spectrum with $\Gamma = 0.25$, $h = 0.7$, and $\sigma_8 = 0.84$, and we implicitly assume that linear theory still holds at this epoch (at least for its predictions on the ratio δ_B/δ_D) and that the derived

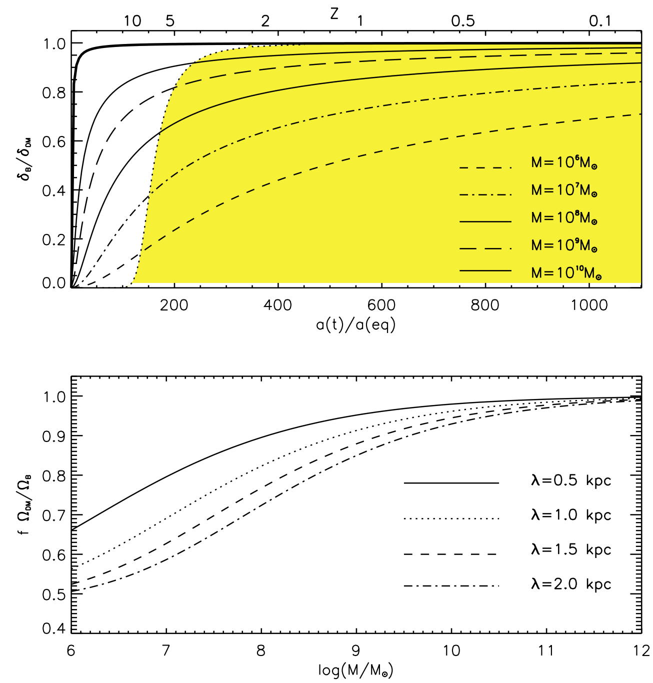

FIG. 2 (color online). Upper: time evolution of the fraction δ_B/δ_D predicted by our model ($\alpha = -1$, $\lambda = 1.1$ kpc) for perturbations corresponding to galaxies of different masses. The scale-invariant standard result is also plotted (thick line). The shaded region represents the postturnaround epoch. Lower: baryon fraction at the turnaround epoch in units of its mean cosmological value Ω_B/Ω_D as a function of the mass of the collapsed object and for different values of λ.

f is a good estimate for the baryon fraction in the final collapsed object. From the lower panel in Fig. 2 one may see that the Yukawa-like potential acts in such a way to avoid that the universal gas fraction (Ω_B/Ω_D) be locked up in low mass clumps at high redshift. For example, we predict $f \sim 0.5\Omega_B/\Omega_D$ in galaxies having $M = 10^6 M_{\odot}$. We note, however, that to fully exploit the simplicity of linearized equations, we have neglected the statistic of the halo hierarchical merging.

Our phenomenological assumption lacks an explanation in terms of fundamental physics. The large absolute value of α tends to rule out the interpretation of the Yukawa contribution in terms of a scalar-field-mediated force. In a scalar-field scenario, in fact, the strength parameter evaluates $\alpha = \alpha_B \alpha_D$, where α_B and α_D are the couplings of the scalar to baryonic and dark matter, respectively (see, e.g., [26]). Since the scalar-baryon coupling is constrained to be $|\alpha_B| \lesssim 10^{-2}$ by very long baseline radiointerferometry measurements (see, e.g., [27]), a dramatic short-range modification of gravity of the order of $\alpha_D^2 \gtrsim 10^4$ in the pure dark matter sector could not be avoided, at least under the minimal assumption of a universal scalar-dark coupling α_D.

In summary, we have argued that the coupling between DM and baryons vanishes in the small distance limit, and it can be effectively described by adding a Yukawa-like contribution with universal parameters $\alpha \sim -1$, $\lambda \sim$ 1 kpc to the standard gravitational potential. Our model does not affect the relation between dark and visible matter on *large* cosmological scales (i.e., the dynamics of large galaxies and clusters), but interestingly it successfully alleviates some inconsistencies between observations and CDM theoretical predictions on kpc scales. In particular, (a) the analysis of the H_α rotation curves of LSB galaxies shows that the central dark matter density distribution predicted under the assumption of a Yukawa potential well ($\beta = -1.35 \pm 0.05$) is in excellent agreement with the cuspy profile derived in collisionless CDM simulations. In particular, the α best fitting values suggest that, independently of the adopted Yukawa model, the gravitational interaction between these two classes of matter is totally suppressed in the small distance limit. (b) This potential offers an interesting cosmological mechanism to segregate the quantity of baryons that falls into primordial dark matter perturbations as a function of the fluctuation mass; this fact may be used to relax estimates of the efficiency of various feedback mechanisms proposed to suppress the overproduction of dwarf galaxies.

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