Effect of gravitational field self-interaction on large structure formation

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We check whether General Relativity’s field self-interaction alleviates the need for dark matter to explain the universe’s large structure formation. We found that self-interaction accelerates sufficiently the growth of structures so that they can reach their presently observed density. No free parameters, dark components or modifications of the known laws of nature were required. This result adds to the other natural explanations provided by the same approach to the, *inter alia*, flat rotation curves of galaxies, supernovae observations suggestive of dark energy, and dynamics of galaxy clusters, thereby reinforcing its credibility as an alternative to the dark universe model.

I. INTRODUCTION

The essential role of dark matter in the growth of galaxies and other large structures constitutes an important evidence for the reality of that dark component of the universe. Cosmic microwave background (CMB) anisotropy data show [1] that at recombination time ($t \approx 3.7 \times 10^{-4}$ Gyr, or redshift $z \approx 1100$), the fractional density fluctuations $\delta$ that will evolve to form the large structures have typical magnitudes of $\approx 10^{-5}$. Modeling their evolution via the Jeans collapse mechanism and assuming solely baryonic matter yield, for the present times, $\delta \approx 10^{-2}$. This is 2 orders of magnitude lower compared to observations. Dark matter solves this problem since its lack of electromagnetic interaction allows it to start to coalesce without impediment from electromagnetic pressure, and therefore significantly earlier than visible matter whose growth is then accelerated by the relatively denser dark matter halos.

Although this model is generally successful in describing the distribution of the universe’s matter density, it predicts too many dwarf galaxies and globular clusters [2]. Furthermore, unease is growing from the absence of direct [3] or indirect [4] detection of dark matter particles, especially since these searches have largely exhausted the parameter space of the most natural and compelling theories, e.g., SUSY, that provide suitable candidates [5]. These problems motivate theories alternate to dark matter. While in principle those need not solve all the questions involving dark matter single-handedly, solving these questions consistently would strongly support the plausibility of an alternate theory. Foremost among the questions to be addressed is the growth of large structures. In this article, we discuss whether the self-interaction (SI) of gravitational fields, a well-known feature of General Relativity (GR), may help resolve the problem of the too slow growth of large structures, in the absence of dark matter. Without modifying the known laws of nature or assuming exotic matter, GR’s SI already provides natural solutions for several observations linked to dark matter, namely (1) the flat rotation curves of galaxies [6–8]; (2) the tight empirical relation between the accelerations measured in galaxies and the accelerations calculated from the galactic baryonic contents [9]; (3) the internal dynamics of galaxy clusters, including the Bullet Cluster [6]; (4) the Tully-Fisher relation [6, 10]; and (5) the correlation between the ellipticity of early-type galaxies and their inferred dark mass [11]. Furthermore, and especially relevant for this article, when GR’s SI are accounted for in the universe’s evolution equation, no dark energy is needed [10]. Because the GR’s SI approach connects straightforwardly dark matter and dark energy (see next section), the formalism used in Ref. [10] can be directly applied to the problem of structure formation.

In the next section, we recall the origin of GR’s SI and summarize the similarities between GR and the Strong Interaction, whose SI effects are well-known and can thus guide the study of GR’s SI. Next, using the global formalism of Ref. [10], we show how GR’s SI accelerates the growth of large structures, thereby offering an explanation of their formation without requiring dark matter.

II. FIELD SELF-INTERACTIONS IN GENERAL RELATIVITY AND THE STRONG INTERACTION

Besides their fundamentally different interpretation of the nature of gravitation, GR and Newton’s gravity also crucially differ in that GR is non-linear. This can be traced to field SI once space-time curvature is interpreted in terms of fields. GR can be formalized by the Einstein-Hilbert Lagrangian density,

$$\mathcal{L}_{GR} = (\det g_{\mu\nu})^{1/2} g_{\mu\nu} R^{\mu\nu}/(16\pi G),$$



(1)

with $g_{\mu\nu}$ the metric, $R_{\mu\nu}$ the Ricci tensor and $G$ the gravitational constant. The gravitational field $\varphi_{\mu\nu}$ originating from a unit mass source is the variation of $g_{\mu\nu}$ with respect to a constant metric $\eta_{\mu\nu}$: $\varphi_{\mu\nu} = (g_{\mu\nu} - \eta_{\mu\nu})/\sqrt{M}$, where $M$ is the system mass. Expanding $\mathcal{L}_{GR}$ in term of $\varphi_{\mu\nu}$ yields, in the pure field case [12]:

$$\mathcal{L}_{GR} = [\partial \varphi \partial \varphi] + \sqrt{16\pi MG} [\varphi \partial \varphi \partial \varphi] + 16\pi MG [\varphi^2 \partial \varphi \partial \varphi] + \cdots,$$



(2)
where \( [\varphi^n \partial_n \varphi] \) represents a sum of Lorentz-invariant terms of the form \( \varphi^n \partial_n \varphi \). Newton’s gravity is given by \( \mathcal{L}_{GR} \) truncated to \( n = 0 \), with \( [\partial_\nu \varphi_0 \varphi] = 0 \). The flat metric and \( \partial^0 \varphi_{00} = 0 \). The \( n > 0 \) terms induce field SI.

Another fundamental force displaying SI is the Strong Interaction. It is formalized by quantum chromodynamics (QCD) whose pure field Lagrangian is:

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\mathcal{L}_{QCD} = [\partial_a \phi \partial_a \phi] + \sqrt{\frac{n}{\pi\alpha_s}} \left[ \frac{1}{4} \phi^2 \partial_\phi \right] + \pi \alpha_s \left[ \frac{1}{4} \phi^4 \right] ,
\]

Here, \( \phi_a \) is the gluonic field and \( \alpha_s \) the QCD coupling [13]. Again, a bracket \( [ \] \) indicates a sum of Lorentz-invariant terms, and, in the QCD case, contractions of the color indices. The similarity between \( \mathcal{L}_{GR} \) and \( \mathcal{L}_{QCD} \) makes the latter useful as a guide for GR in its strong regime, since QCD in that regime is well-studied. Like GR, the terms beyond \( [\partial_a \phi \partial_a \phi] \) induce the field SI. They are interpreted in QCD (GR) as arising from the color charges (energy-momentum) carried by gluonic (gravitational) fields, which permit field self-coupling. For QCD the coupling – driven by \( \alpha_s \) is large, making the consequences of field SI prominent. In GR, large \( \sqrt{GM/L} \) values (\( L \) is a characteristic length of the system) enable SI. QCD’s SI strongly increases the interaction between color charges and causes quark confinement. Likewise, GR’s SI increases the gravitational system’s binding compared to Newton’s theory. If the latter is used to analyze galaxy or cluster dynamics, as is commonly done, ignoring the SI-induced intensification of the force then creates a missing (dark) mass problem. The results of Refs. [6]-[8] indicate that SI can sufficiently strengthen the gravitational binding such that no dark matter is required to explain galactic rotation curves or the internal dynamics of galaxy clusters. In QCD, the SI strengthens so much the binding of color sources that they remain confined, i.e. the Strong Interaction is essentially\(^1\) suppressed outside of the system, e.g. outside a nucleon. This can be globally understood from energy conservation: the confined field increases the system’s binding energy, but the field concentration causes its depletion outside of the system. Likewise\(^2\) in gravitational systems, the increased binding due to GR’s SI weakens gravity’s action at large scale. If GR’s SI is ignored, this weakening can then be misinterpreted as a large-scale repulsion, \( v_i z \) dark energy. The effect is time-dependent: as massive structures form, some gravitational fields become trapped in them, weakening their manifestation at larger scale. This implies a direct connection between dark energy and dark matter, particularly between dark energy and the onset of structure formation.

In summary, GR and QCD possess similar Lagrangians whose structure enables field SI. Those are prominent for QCD because \( \alpha_s \) is large. Analogously, they must become important for GR once the system’s \( \sqrt{GM/L} \) is large enough. Performing a Newtonian analysis for massive systems, or using GR assuming isotropy and homogeneity\(^3\) overlooks the effects of SI, resulting in an apparent missing mass inside the systems and an apparent global repulsion at larger scale. The apparent missing mass and global repulsion can then be interpreted as dark matter and dark energy, respectively. The GR SI approach is supported by parallels between QCD’s phenomenology and the observations involving dark matter and dark energy, e.g. the similarity between the hadrons’ Regge trajectories [15] and the galactic Tully-Fisher relation [16], or the stronger (weaker) force manifestation inside (outside) systems, those being either hadrons, galaxies or galaxy clusters. The approach is discussed in detail and quantitatively in [6]-[11]. Here, we study whether it can also explain large structures’ growth.

### III. ROLE OF FIELD SELF-INTERACTION IN LARGE STRUCTURE FORMATION

As summarized above, GR’s SI increases the internal binding of a massive system, i.e. the interaction between components of the system. In the method described in Refs. [6, 7] (a lattice numerical approach), the force strengthening is interpreted as the collapse of field lines into the galactic disk, effectively reducing the 3-dimensional (3D) force to a 2-dimensional (2D) force \( F_{2D} \propto 1/r \). This interpretation mirrors that of QCD for which lattice calculations of static two-body systems show that field lines collapse into 1-dimensional (1D) structures called QCD strings or flux-tubes [17]. The collapse induces a constant force \( F_{1D} \) between the two bodies (\( v_i z \), the static quarks) since the field lines cluster along the segment linking the two bodies. In the disk case, the \( F_{2D} \propto 1/r \) force results from the field lines collapsing in the approximately 2D axially symmetric disk. Finally, a system exhibiting a 3D spherical symmetry would retain a \( F_{3D} \propto 1/r^2 \) force since field lines have no preferred direction of collapse, \( v_i z \) there would be no SI strengthening of the force. In the QCD case, the 1D system displaying \( F_{1D} = \text{const.} \) is composed of a static quark and a static anti-quark. In the gravitational case, a 1D system massive enough to trigger GR’s SI would be that

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\(^1\) The residual Strong Interaction outside a nucleon, e.g. the Yukawa interaction, is much weaker than the quark-quark interaction.

\(^2\) Although energy conservation does not always hold in GR, it does for localized systems such as galaxies or galaxy clusters.

\(^3\) While the universe’s evolution equation derives from GR, the standard approximations of isotropy and homogeneity suppress the SI [6, 9, 11]. This is manifested by the ability to model with surprising accuracy the universe evolution using Newton’s theory [14].
of two galaxies. In that case, interactions will be stronger than the Newtonian expectation\(^4\) and string-like structures akin to QCD’s flux tubes should arise at the intergalactic/galactic cluster scale. This qualitatively agrees with the web structure of the present-time universe and the necessity of enhanced gravitational interaction (or mass density) to explain the growth rate of large structures. In Ref. \cite{8}, a background field method is used to compute GR’s SI effects. The background field represents the total gravitational field of the system and is treated as a space-time curvature. The individual interaction between two particular bodies composing the system is treated as a traditional force (viz a field line density). Just like for light lensing, the space-time curvature focuses the gravitational field lines between the individual bodies forming the system. This increases the field line density i.e. increases the force, like light lensing magnifies the background object’s luminosity. In the case of inhomogeneous systems made of multiple point-like bodies, lensing happens when three bodies are approximately aligned. The alignment is then strengthened and further enhanced, consistent with the previous discussion based on the lattice method and again suggestive of the universe’s web structure.

The SI-enhanced gravitational interaction should hasten the collapse of overdensities and the merging of primordial overdensities or of proto-galaxies, resulting in faster growth rates and a reduced need for dark matter. The formalism of Ref. \cite{10} can be used to quantitatively test this possibility. Ref. \cite{10} points out that the SI-enhanced binding inside massive systems is balanced by reduced gravitational field outside these systems, and shows how this reduction can explain without dark energy the large-\(z\) supernova observations \cite{18}. To show this, the effective large-scale weakening of gravity was folded into a depletion function \(D_M(z)\) that quantifies the average suppression of gravity at large scales, with \(D_M = 0\) indicating full suppression and \(D_M = 1\) none. In particular, the smallness of the density fluctuations and the homogeneity and isotropy of the early universe suppress SI effects at large \(z\). Therefore \(D_M(z) \approx 1\) at large \(z\). In contrast, present times are characterized by a structured universe. If all fields were trapped in structures, then \(D_M(z) \approx 0\) at small \(z\). However, SI effects tend to cancel in symmetric structures and the increasing ratio of elliptical over disk galaxies at late times makes \(D_M(z)\) rise at small \(z\). \(D_M(z)\) from Ref. \cite{10} is shown in the top panel of Fig. 1. \(D_M(z)\) appears in the derivation of the Friedmann equation as a factor to \(G\), once the standard approximations of isotropy and homogeneity of the universe are lifted. \(D_M(z)\) is constructed using the time-dependent fractions of baryonic matter contained in each type of large structure (viz what fractions of the universe’s baryonic matter are contained in galaxies, groups, clusters and superclusters) and the time-dependent ratios of approximately spherical systems to non-spherical systems (e.g. the ratio of elliptical over disk and peculiar galaxies). Specifically, the amount of galaxies formed is modeled in \cite{10} with a Fermi-Dirac (FD) function of width equals to the characteristic period during which galaxies form. The limits of the function, 0 and 1, express full SI effects and overall suppression of them, respectively. Since galaxies are but one of the types of large structures, the FD function is normalized by the relative

\(^4\) For this to occur, the 2-galaxy system should contain at least one elliptical galaxy. Otherwise, field line collapse would happen within the galaxies themselves, thereby trapping most of their gravitational field within their structures, leaving no field outside for the galaxy-galaxy interaction. Thus, we expect reduced interactions between two massive disk galaxies, and enhanced interactions otherwise.
amount of baryonic matter contained in galaxies. $D_M(z)$ is the product of the galactic FD function and that modeled for groups, clusters and superclusters. $D_M(z)$ also contains a correction term that accounts for the suppression of SI effects in approximately spherically symmetric structures. This correction is proportional to the ratio of elliptical to other galaxies. Alternatively to FD functions, we also constructed $D_M(z)$ using linear functions, or convolutions of an Heavside function with a Gaussian function. Comparing these $D_M(z)$ to the one obtained with FD functions shows that dependence on the choice of function is small compared to the uncertainty band of $D_M(z)$.

Since $D_M$ quantifies the global large-scale suppression of gravity stemming from the strengthening of the structure internal binding, the strengthening behaves like $D_M^{-1}$. That is directly given by $D_M^{-1}$ is the simplest assumption, which we shall use. Since by definition $0 \leq D_M \leq 1$, then $D_M^{-1} \geq 1$, in agreement with the SI-increase of system binding. For example, the present value $D_M^{-1} \approx 4.2$ (Fig. 1, bottom panel) implies that large structures are bound on average 4.2 times more than a Newtonian analysis with only baryonic matter would indicate. Before calculating the structure growth accounting for GR’s, we first recall the evolution equation of a baryonic overdensity $\delta(t)$ without SI. It stems from the continuity and Euler equations, with Newton’s potential used in the latter:

$$\frac{d^2\delta(t)}{dt^2} + 2\frac{dR(t)/dt}{R(t)} \frac{d\delta(t)}{dt} + (c_s(t)^2 k^2 - 4\pi G\rho_0(t))\delta(t) = 0,$$

(4)

where $R$ is the overdensity radius, $c_s$ the sound speed, $k$ the overdensity wavevector and $\rho_0$ the average density. Since $D_M^{-1}$ represents the average increase of the gravitational binding inside systems, it factors the term proportional to $G$, just like in Ref. [10] $D_M$ factors $G$ in the Friedmann equation. Eq. (4) thus becomes:

$$\frac{d^2\delta(t)}{dt^2} + 2\frac{dR(t)/dt}{R(t)} \frac{d\delta(t)}{dt} + (c_s(t)^2 k^2 - 4\pi G D_M^{-1}(t)\rho_0(t))\delta(t) = 0.$$

(5)

For the matter dominated epoch $c_s^2 k^2 \ll 4\pi G \rho_0$ and for a flat universe, Eq. (5) becomes:

$$\frac{d^2\delta(t)}{dt^2} + \frac{4}{3t} \frac{d\delta(t)}{dt} - \frac{2D_M^{-1}(t)}{3t^2} \delta(t) = 0.$$

(6)

The uncertainty band for $D_M(z)$ shown in Fig. 1 was obtained in Ref. [10] with the usual procedure of propagating the systematic uncertainties of the parameters on which $D_M(z)$ depends. Specifically, the widths and centers of the FD functions, the fractions of baryonic matter contained in the different structure types, and the ratio of elliptical to other galaxies, are systematically varied within ranges determined by their respective uncertainties. This provides a distribution of $D_M(z)$ curves around the nominal $D_M(z)$. The envelope of the distribution is taken as the uncertainty band on $D_M(z)$. The procedure conservatively assumes that the individual parameters’ systematic uncertainties add linearly. With such procedure, the band cannot be expressed in closed form. Since a closed form is convenient for the present work, we parameterized $D_M$ and found that the following expressions fit well the upper and lower limits of the band, respectively:

$$D_M(z)^{up} = 0.84 \left(0.9 - \frac{1}{1 + e^{\left(c_s^{-4} + 3\pi/t\right)/z}} + \frac{0.17}{z + 0.3}\right),$$

$$D_M(z)^{low} = 0.80 \left(0.915 - \frac{1}{1 + e^{\left(c_s^{-4} + 5\pi/2\right)/z}} + \frac{0.024}{z + 0.2}\right).$$

(7)

The nominal $D_M(z)$ has a closed form but for convenience, we parameterize it with a form similar to those above:

$$D_M(z)^{nominal} = 0.76 \left(1 - \frac{1}{1 + e^{\left(c_s^{-4} - 3\pi/4\right)/z}} + 0.25e^{-5z}\right).$$

(8)

Eqs. (7) and (8) are traced by solid lines in Fig. 1, top panel. $D_M(z)$ is re-expressed with $t$ and inverted to obtain $D_M^{-1}(t)$, shown in bottom panel of Fig. 1. With it, we solved numerically Eq. (6) using an initial overdensity $\delta = 2 \times 10^{-5}$ at $t \approx 0.37$ Myr ($z \approx 1100$). This corresponds to CMB temperature fluctuations of 55 $\mu$K, typical of the observed CMB data [1] which shows temperature fluctuations reaching 75 $\mu$K and 50 $\mu$K for the main and second acoustic peaks, respectively. The time evolution of $\delta(t)$ from $t = 0.37$ Myr up to present time is shown in Fig. 2. The solid line is the evolution including SI, Eq. (6), and the band is the uncertainty due to $D_M^{-1}$. The dashed line is the evolution without SI, Eq. (4). The perturbation $\delta(t)$ is evolved as long as $\delta(t) < 1$. Once $\delta(t) \sim 1$, Eq. (4) breaks down and non-linear effects arise. These non-linearities are of different origin than those induced by GR’s SI since they also appear with Newton’s gravity, a linear theory. We do not need to consider here the non-linear regime that supersedes Eq. (4) since the global perturbative treatment of Eq. (6) is sufficient to conclude that due to SI increasing locally the action of gravity, overdensities can reach the observed present $\delta > 1$ values, without need of dark matter.

The picture for structure growth that emerges from the result showed in Fig. 2 is that at early times, SI did not influence the Jeans collapse mechanism since the initial overdensities were spherical. Mergers of overdensities would also not be significantly enhanced since density anisotropies would be too small to trigger the onset of SI. At later times, the overdensities lose their spherical symmetry due to mergers and radiative energy dissipation. The SI-enhanced internal binding then accelerates local collapses. As anisotropies become denser, merging rates increase,
FIG. 2: Time-evolution of a baryonic overdensity $\delta$. The initial value of $\delta$ at the recombination time, $t \approx 3.7 \text{ Gyr}$, is $2 \times 10^{-5}$. The band shows the evolution including field SI effects, with the central solid line corresponding to the nominal $D_M^{-1}(t)$. The dashed line is the evolution without SI. In neither case, dark matter has been assumed.

especially for overdensities that had so far retained their spherical shape. The quantitative analysis shows that the SI-enhanced gravitational interaction is sufficient to form structures reaching the present-day densities, without requiring dark matter. We have considered here the time-evolution of $\delta$ and not the related subject of matter’s spatial distribution. As shown in Ref. [10], the same formalism also yields a position of the peak of the matter power spectrum of $k_{eq} \simeq 0.014 \text{ Mpc}^{-1}$, in agreement with observations.

IV. SUMMARY

The consistency of the standard $\Lambda$-CDM model of the universe in explaining many observations that would be otherwise problematic is a compelling argument for the existence of dark matter and dark energy. Yet, there are good reasons for studying alternatives to $\Lambda$-CDM, e.g. the lack of detection of dark particles, the dwindling support from theories beyond the standard model of particle physics, observations that challenge the dark matter model such as [19], lack of observations of $\Lambda$-CDM predictions such as the dwarf galaxy problem, or the Hubble tension [20]. The credibility of an alternative approach is enhanced if, like for $\Lambda$-CDM, it can consistently explain the otherwise puzzling cosmological observations. One alternative approach proposes that these observations are explained by the self-interaction of gravitational fields in General Relativity. It naturally explains the galactic rotation curves [6]-[8], the supernovae observations suggestive of dark energy [10], the tight empirical relation between baryonic and observed accelerations [9, 19], the dynamics of galaxy clusters [6] and the Tully-Fisher relation [6, 10, 16]. The explanation is natural in the sense that a similar phenomenology is well-known in the context of QCD, a fundamental force whose Lagrangian has the same structure as that of General Relativity. Crucially, no free parameters are necessary, nor exotic matter or fields, nor modifications of the known laws of nature. In this article, we checked whether the approach also explains the formation of large structures. We found that field self-interaction strengthens sufficiently the gravitational force so that the small CMB inhomogeneities can grow to the density presently observed. Again, no free parameters were needed: the function that globally quantifies the effect of field self-interaction had been previously determined in Ref. [10] in the context of the a priori unrelated topic of dark energy.

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