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Observational constraints on the unified dark matter and dark energy model based on the quark bag model

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ABSTRACT

In this work we investigate if a small fraction of quarks and gluons, which escaped hadronization and survived as a uniformly spread perfect fluid, can play the role of both dark matter and dark energy. This fluid, as developed in [1], is characterized by two main parameters: β, related to the amount of quarks and gluons which act as dark matter; and γ, acting as the cosmological constant. We explore the feasibility of this model at cosmological scales using data from type Ia Supernovae (SNeIa), Long Gamma-Ray Bursts (LGRB) and direct observational Hubble data. We find that: (i) in general, β cannot be constrained by SNeIa data nor by LGRB or $H(z)$ data; (ii) γ can be constrained quite well by all three data sets, contributing with $\approx 78\%$ to the energy–matter content; (iii) when a strong prior on (only) baryonic matter is assumed, the two parameters of the model are constrained successfully.

1. Introduction

A huge amount of high-quality observational data collected so far has made the acceleration of the universe an indisputable fact [2–10]. Such unexpected behaviour has been commonly attributed to an unknown entity acting as a counter-gravitating fluid, dark energy (DE), and has motivated the bloom of an impressive amount of cosmological models which may be able to elucidate its nature. So far, the so-called ΛCDM model is the most accepted cosmological model, and it is based on the well known cosmological constant; however, it still suffers from theoretical drawbacks that make it difficult to reach a conclusive consensus.

Many theoretical proposals can be found which attempt to throw some light on the cosmic acceleration mystery, either trying to address its very origin, or (more modestly) attempting at a compelling description of the recent history of our accelerated universe. Some proposals are based on scalar fields, either canonical, such as quintessence [11,12], or with weirder features, such as k-essence [13] or phantom [14] models. Others have an extra-dimensional spirit and invoke braneworlds [15,16].

Dark matter (DM) is the other main, yet unknown, component of the Universe, and it is necessary to produce enough gravitational attraction on certain scales crucial to structure formation. Some of the proposals for the description of accelerated cosmologies rely on (phenomenological) unified pictures (so-called unified dark matter models) where a unique exotic fluid accounts for the whole dark sector composed by DE and DM. If we specifically refer to unified dark matter models, then let us remind that most of them resort to the generalized Chaplygin gas (GCG) [17–19], but one can find other (also phenomenological) proposals as those in [20,21].

The list of (accelerated) scenarios can be completed with many other cases. But if we use the popularity criterion among those additional proposals, then modifications to the General Relativity Lagrangian stand out [22–25]. Nevertheless, see [26–33] for reviews on DE models, which provide a wide perspective on the topic of current cosmic acceleration in general.

In general we have a vast collection of set-ups which are quite different in their underlying physics, and although many of them (including the *concordance* ΛCDM model) have a great compliance with observational data, none of them is full proof.

On the other hand, the proposal by [1], which can be considered as part of the stream of unified dark matter models, has been suggested to explain the nature of DM and the present cosmic acceleration. Such suggestion arises from the hypothesis that a small part of quarks and gluons did not yield to hadronization, and resisted either as isolated aggregates of quark–gluon *nuggets* (QNs) or as a perfect fluid in the form of a quark–gluon plasma (QGP) (uniformly spread on cosmological scales). There have been several works scrutinizing and supporting this guess [34–37], and the idea followed that the QNs could be a good candidate for DM.

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In fact, a recent perturbative analysis [38], reached the conclusion that compatibility with observations was possible (for a mechanical perspective on this topic see [39–41]).

In contrast, the QGP perfect fluid has not gathered the same interest. A recent work [42] explored the possibility that the QGP fluid acted as DM in galactic halos concluding that the corresponding rotation curves were reasonable. At the cosmological level, a QGP fluid was first considered to mimic DM in [1].

Clearly, the theoretical perspective makes the quark bag an attractive one, as it opens the door to an answer to the nature of the two dark components of the universe without resorting to exotic physics.

In previous reference the compliance with observations was carried out in an inverse approach, assuming facts hinted by observations the necessary properties of the quark models were derived. But it is absolutely mandatory to work reversely, that is, to assume the model and then to contrast its theoretical predictions with the observational data. This has to be done in an statistically proper way, beyond quantitative sketches. A thorough study will allow to ascertain whether the model is worth exploring further. This is precisely the objective of this work: to establish the viability of the quark bag proposal, which attempts to explain DE and DM in a unified fashion. In order to do that, we perform a standard statistical analysis by using the following astrophysical probes: type Ia Supernovae (SNeIa), Long Gamma-Ray Bursts (GRBs) and observational Hubble data. In the next section, we describe briefly the main conclusions of each scenario sketched in [1]. In Section 3, we present the observational data samples used in our analysis and finally, in Section 4, we describe and discuss our findings.

2. Cosmological scenarios from QGP

In this section we shall focus on the cosmological consequences of the two theoretical scenarios proposed in [1], i.e. QNs and QGP. These two scenarios begin to be valid at the matter dominated era and then remain so forever. Even though these two set-ups are based on the quark bag equation of state, we will show that each of them has different cosmological implications, see [1] for further details. Besides, following the same reference, we assume the quark bag fluid is accompanied by a cosmological constant.

Notice also that throughout this analysis we have considered $\Omega_K = 0$ as has been recently confirmed by [10].

2.1. Quark nuggets (I)

This scenario stems from the modification of the quark bag equation of state (EoS) suggested in [43]. From such modified EoS one gets the following Hubble function:

$$\frac{H^2}{H_0^2} = \left[\beta\left(\frac{a_0}{a}\right)^3 + \gamma\left(\frac{a_0}{a}\right)^{9/4}\right]^{4/3} + \Omega_m\left(\frac{a_0}{a}\right)^3 + \Omega_\Lambda, \tag{1}$$

where, in principle, the Ω_m term corresponds to the usual matter content at present (baryons + DM), and Ω_Λ to the cosmological constant. Notice that the term inside the brackets behaves at early times ($a \ll a_0$) like radiation, $\sim \beta a^{-4}$, and at later times ($a \gg a_0$) like matter, $\sim \gamma a^{-3}$.

Concerning the cosmological implications of this model, not many conclusions can be drawn. First, QNs alone cannot drive cosmic acceleration, the cosmological term is necessary for that. On the contrary, when $\Omega_\Lambda = 0$ is assumed, the cosmic acceleration is achieved only if $\beta < 0$, which leads to inconsistencies in the model because β is positive definite, see [1] for further details.

On the other hand, assuming the presence of the cosmological constant, and by considering $\beta = 0$ (or the weaker condition $\beta \ll \gamma$, which is quite realistic, if the term proportional to β acts as radiation), one easily obtains:

$$\Omega_m^{\text{eff}} = \gamma^{4/3} + \Omega_m. \tag{2}$$

In this case, Ω_m could play only the role of baryonic matter, and $\gamma^{4/3}$ that of DM. Unfortunately it is quite clear that the use of observational data at the background level will not allow to distinguish between this model and the standard literature results. Phenomenologically all remains very much the same, only the theoretical interpretation about the origin of the model is new.

A more interesting case arises when one chooses $\beta \neq 0$ and then wonders whether γ assumes values compliant with the proposed assumption of quarks acting like dark matter. Let us recall that the weaker condition $\beta \ll \gamma$ could realistically hold, if the term containing β acted as radiation. But the role of γ as a possible contribution to DM has to be verified. We will study this case in the next sections.

2.2. Quark nuggets (II)

The cosmological implications of this model follow from the assumption of the original quark-bag EoS, see Section 3.2 of [1]. The Hubble function is given by:

$$\frac{H^2}{H_0^2} = \beta\left(\frac{a_0}{a}\right)^4 + \gamma\left(\frac{a_0}{a}\right)^3 + \Omega_m\left(\frac{a_0}{a}\right)^3 + \Omega_\Lambda. \tag{3}$$

Clearly, the main difference with model I, is the absence of any interaction between the β and the γ terms. As can be seen from Eq. (3), this scenario contains standard (i.e. isolated) radiation and matter components, but their origin is from the thermodynamical properties of QNs. Obviously, this model goes to the ΛCDM case when one assumes that the effective matter content is $\Omega_M^{\text{eff}} = \gamma + \Omega_m$, where Ω_m could play the role of only baryonic matter. On the other hand, it is not possible to explain current cosmic acceleration without the cosmological constant, whereas the QNs may be candidates for DM only, but again, the situation is observationally indistinguishable from other classical interpretations.

2.3. Quark–gluon-plasma-like perfect fluid (I)

This model assumes that the perfect fluid composed by a quark–gluon plasma has thermodynamical properties derived from the modified quark-bag EoS proposed by [43]. The Hubble function, see Section 4.1 of [1] for further details, is given by:

$$\frac{H^2}{H_0^2} = \left[\beta\left(\frac{a_0}{a}\right)^3 + \gamma\right]^{4/3} + \Omega_m\left(\frac{a_0}{a}\right)^3 + \Omega_\Lambda. \tag{4}$$

In the particular case of $\beta = 0$, the ΛCDM model is clearly restored and the term containing $\gamma^{4/3}$ might play the role of the cosmological constant. Thus, in principle one could set $\Omega_\Lambda = 0$, and a satisfactory fit to cosmological data would be possible, but quarks would not contribute to DM.

In [1], the more interesting $\beta \neq 0$, $\Omega_\Lambda = 0$ case is considered, upon the hypothesis that Ω_m *should* correspond only to baryonic matter, while the β and γ parameters *might* account for the nature of DM and DE, respectively. We will explore the feasibility of this model in more detail in the following section.

2.4. Quark–gluon plasma like perfect fluid (II)

This is our last scenario, with the Hubble function given by:

$$\frac{H^2}{H_0^2} = \beta\left(\frac{a_0}{a}\right)^4 + \gamma + \Omega_m\left(\frac{a_0}{a}\right)^3 + \Omega_\Lambda. \tag{5}$$