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Bigravitational origin of dark matter

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Observational evidence for dark matter is limited to gravitational effects. Dedicated searches have yielded null results, challenging the most popular models. This can be explained if cold dark matter is a massive spin-2 particle and, thus, a manifestation of gravity itself. In the unique consistent theory for a massless and a massive spin-2 field, the latter can be heavy, stable on cosmological scales, and produced with correct abundance, and its matter coupling is naturally as weak as the gravitational one. The theory satisfies current gravity tests, and we suggest several gravitational signatures.

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I. THE PROBLEM OF DARK MATTER

Approximately 85% of the matter content of the Universe is in the form of dark matter (DM), the origin and properties of which still remain unknown. The existence of DM in our Universe is inferred from its gravitational effects in a number of complementary ways: galactic dynamics (rotation curves and velocity dispersions), gravitational lensing, positions and shapes of the cosmic microwave background peaks, observation of the baryon acoustic oscillations, matter power spectra, and simulations of structure formation [1].

Within the current paradigm, DM is modeled as a cold relic density of an unknown particle produced in the early Universe. DM models rely on several different production mechanisms, but they usually introduce a new, very weak coupling to baryonic matter. This hypothetical interaction motivates the many current and future dedicated searches aimed at the discovery of DM particles in collider, direct, and indirect detection experiments [1–5].

In spite of such extensive effort, DM has thus far remained very elusive, and the experimental null results severely constrain the parameter spaces of viable DM models. Taken at face value, this outcome may, in fact, point towards the need for a paradigm shift: DM is part of gravity itself, and its coupling to Standard Model (SM) particles is suppressed by the Planck mass. In this article, we demonstrate that such a DM particle is automatically built into the only known consistent extension of general relativity (GR) to an additional interacting massive spin-2 field.

It should be emphasized that our novel model is not constructed in order to explain the observation of DM. Instead it corresponds to the only consistent description of gravitationally interacting massive spin-2 fields and thus it emerges naturally from fundamental principles of field theory. It differs substantially from most other DM models and, in particular, it explains the absence of direct detection signals. In this article, we introduce the idea of spin-2 DM, derive constrains on its parameter space and develop first alternative ideas on how to test the model.

II. GHOST-FREE BIMETRIC THEORY

A recent breakthrough in the physics of gravitation was the construction of ghost-free bimetric theory (see [6] for a review). This theory contains, in addition to the usual massless graviton, a second propagating spin-2 particle with nonzero mass. Its action describes two dynamical tensor fields $g_{\mu\nu}$ and $f_{\mu\nu}$ [7],

$$S = m_g^2 \int \mathrm{d}^4x \Big[\sqrt{|g|}R(g) + \alpha^2\sqrt{|f|}R(f) - 2m^2\sqrt{|g|}V(g^{-1}f)\Big] + S_{\mathrm{matter}}, \quad (1)$$

where m_g and αm_g are the mass scales setting the interaction strengths of the two tensors, while m sets the mass scale for the massive spin-2 field. The consistency of the theory dictates the form of the potential $V(g^{-1}f)$ [8,9],

$$V\left(\sqrt{g^{-1}f}\right) \coloneqq \sum_{n=0}^{4} \beta_n e_n\left(\sqrt{g^{-1}f}\right), \quad (2)$$

where β_n are five free parameters two of which, β_0 and β_4, act as vacuum energy terms for $g_{\mu\nu}$ and $f_{\mu\nu}$ respectively, and $e_n(S)$ are the elementary symmetric polynomials of the square-root matrix $S = \sqrt{g^{-1}f}$. They can be defined via the unit weight totally antisymmetric product,

$$e_n(S) = S^{\mu_1}_{[\mu_1} \cdots S^{\mu_n}_{\mu_n]}. \tag{3}$$

The absence of ghosts requires that SM matter couples only to one of the metrics in $S_{\rm matter}$. Without loss of generality, we will choose the physical metric to be $g_{\mu\nu}$. This then determines the geodesics which SM matter follows and, as we will see, it is in general a mixture of the massless and massive spin-2 modes.

The propagating degrees of freedom of the theory can be read off the action expanded up to quadratic order in the fluctuations $\delta g_{\mu\nu} = g_{\mu\nu} - \bar{g}_{\mu\nu}$ and $\delta f_{\mu\nu} = f_{\mu\nu} - \bar{f}_{\mu\nu}$ around equal backgrounds $\bar{f}_{\mu\nu} = \bar{g}_{\mu\nu}$. These backgrounds correspond to maximally symmetric solutions of the bimetric equations of motion with cosmological constant [10],

$$\Lambda = m^2(\beta_0 + 3\beta_1 + 3\beta_2 + \beta_3). \tag{4}$$

After diagonalization, the quadratic action has the form

$$S_{(2)} = \frac{1}{2}\int d^4x \bigg[\delta G_{\mu\nu}\mathcal{E}^{\mu\nu\rho\sigma}\delta G_{\rho\sigma} + \delta M_{\mu\nu}\mathcal{E}^{\mu\nu\rho\sigma}\delta M_{\rho\sigma} - \frac{m_{\rm FP}^2}{2}(\delta M^{\mu\nu}\delta M_{\mu\nu} - \delta M^2) - \frac{1}{m_{\rm Pl}}(\delta G^{\mu\nu} - \alpha\delta M^{\mu\nu})T_{\mu\nu}\bigg], \tag{5}$$

where the kinetic operator $\mathcal{E}_{\mu\nu}{}^{\rho\sigma}\delta G_{\rho\sigma}$ is the linearized Einstein tensor including cosmological constant terms. The canonically normalized massless and massive eigenstates are, respectively,

$$\delta G_{\mu\nu} = \frac{m_{\rm Pl}}{1+\alpha^2}(\delta g_{\mu\nu} + \alpha^2\delta f_{\mu\nu}), \tag{6a}$$

$$\delta M_{\mu\nu} = \frac{\alpha m_{\rm Pl}}{1+\alpha^2}(\delta f_{\mu\nu} - \delta g_{\mu\nu}). \tag{6b}$$

The quadratic theory then contains a massless graviton $\delta G_{\mu\nu}$, which mediates standard gravitational interactions with Planck mass $m_{\rm Pl} \equiv m_g\sqrt{1+\alpha^2}$ and an additional massive spin-2 field $\delta M_{\mu\nu}$ whose Fierz-Pauli mass $m_{\rm FP}$ is given by

$$m_{\rm FP}^2 = m^2(1+\alpha^{-2})(\beta_1 + 2\beta_2 + \beta_3). \tag{7}$$

Notice that α simply quantifies the mixing between the original metrics $g_{\mu\nu}$ and $f_{\mu\nu}$ and that an overall scale in the β_n parameters can be absorbed into the mass scale m.

Following an idea suggested in [6], we show here that $\delta M_{\mu\nu}$ can behave as a cold DM particle with mass $m_{\rm FP}$. On the other hand, as the particle arises from the gravitational sector, it contributes to gravitational interactions with an effective Planck mass $m_{\rm Pl}/\alpha$. However, for large mass $m_{\rm FP}$, these interactions are exponentially suppressed by the Yukawa shape of the resulting potential and their effect is practically negligible on astrophysical scales.

III. THE GR LIMITS

In general, bimetric theory introduces modifications to known classical solutions of general relativity (GR) at all energy scales, due to the presence of extra propagating degrees of freedom. Such modifications are tightly constrained, in particular by Solar System tests of gravity [11]. These are usually evaded by invoking the Vainshtein mechanism, which restores general relativity by means of nonlinear self-interactions [12], provided the mass $m_{\rm FP}$ is tuned to tiny values. In principle, however, there exist two independent parameter limits which restore GR for static solutions in the linear regime (see details in [13]), namely $m \to \infty$ and $\alpha \to 0$. In these parameter regions, bimetric theory automatically passes Solar system tests of GR without invoking the Vainshtein mechanism or any other sort of screening. Moreover, in the case $\alpha \to 0$, all solutions for the physical metric $g_{\mu\nu}$ (not only the static ones) come arbitrarily close to those of Einstein's equations [14–16]. It is also known that instabilities of black holes [17] and in cosmological perturbation theory [16] are avoided in the limit of small α. The interesting and nontrivial result that we obtain below is that the massive spin-2 degrees of freedom remain coupled to gravity in both the $m \to \infty$ and $\alpha \to 0$ limits. The massive particle continues to gravitate with the same strength as ordinary baryonic matter and can therefore constitute a suitable DM candidate.

The fact that GR is restored for $\alpha \to 0$ is already suggested by the quadratic action (5): in this limit the massive fluctuation $\delta M_{\mu\nu}$ decouples from matter and the massless field $\delta G_{\mu\nu}$ coincides with the physical metric $\delta g_{\mu\nu}$. Notice also that, in principle, a large value for the DM mass $m_{\rm FP}$ in Eq. (7) can be achieved either by suppressing α or by increasing m.

In order to ensure that our model passes all tests of GR, in this article we concentrate on the parameter region where $\alpha \ll 1$. The features of the complementary regime characterized by $\alpha \sim 1$ and large values of the mass scale m are briefly discussed below, and will be analyzed in detail in a follow-up work [18].

A. Large spin-2 mass

Since its formulation, bimetric theory has often been studied in context of the dark energy (DE) problem. Hence, the mass scale m of the spin-2 particle is typically assumed to be on the order of the Hubble scale H_0. Whereas this assumption avoids fine-tuning the present scale of cosmic acceleration, a value of $m \sim H_0$ is neither a theoretical nor an observational requirement and larger mass values can be considered when the DE problem is addressed in a different way. In this case, the β_n parameters in (4) need to be fine-tuned to produce a small Λ.

For $m \gg H_0$ the Compton wavelength of the heavy spin-2 is very small, hence the associated nonlinear effects are confined to scales that are inaccessible by current laboratory or astronomical tests of GR. In fact, bimetric theory introduces modifications to known classical GR solutions in the weak-field linear regime, i.e. at large scales, which are suppressed by at least a factor of $\exp(-m_{\rm FP} r)$ [13]. This implies that Solar System tests will be automatically satisfied for large values of m, corresponding to large $m_{\rm FP}$. Notice that, in contrast, linear massive gravity with one propagating graviton in the same regime leads to physical predictions different from those of linearized GR [19,20].

On top of that, the instabilities which generically arise in the cosmological perturbation theory of bimetric theory appear at a much higher energy scale in the large mass limit [21]. This relegates the associated nonperturbative effects to earlier unobservable cosmological epochs which, as mentioned above, can also be achieved for small values of α [16].

Thus, to summarize, an additional spin-2 field with a large mass is cosmologically viable and yields well-behaved background solutions which satisfy all the Solar System tests of gravity to the current precision.

IV. VALIDITY OF PERTURBATIVE EXPANSION

One may worry that, for small values of α, the theory enters a nonperturbative regime, where the massive mode is strongly coupled. We demonstrate here that this is not the case and that the theory remains weakly coupled within the energy regimes of interest.

The inverse relations between mass and interaction eigenstates in (6) read

$$\delta g_{\mu\nu} = \frac{1}{m_{\rm Pl}}(\delta G_{\mu\nu} - \alpha \delta M_{\mu\nu}), \tag{8a}$$

$$\delta f_{\mu\nu} = \frac{1}{m_{\rm Pl}}(\delta G_{\mu\nu} + \alpha^{-1} \delta M_{\mu\nu}). \tag{8b}$$

A general vertex of the schematic form $\delta g^k \delta f^n$ in the perturbative expansion of the action around equal backgrounds therefore gives (neglecting numerical factors and tensor structure),

$$\delta g^k \delta f^n \sim \sum_{s=0}^{k} \sum_{r=0}^{n} \frac{\alpha^{s-r}}{m_{\rm Pl}^{k+n}} \delta G^{k+n-r-s} \delta M^{r+s}. \tag{9}$$

Given that $r \leq n$, every enhancing factor of α^{-1} necessarily appears with at least one suppressing factor of $m_{\rm Pl}^{-1}$. This implies that, for energies and field values $E \ll \alpha m_{\rm Pl}$, the theory remains perturbative. We stress that, in particular, strong coupling does not arise in the energy regime $E \ll \alpha m_{\rm Pl}$.

More careful considerations show that, for energies $E \ll \alpha m_{\rm Pl}$, the vertices with at most six powers of the fluctuations deliver the dominant effects of interactions among the massive and massless spin-2 field and thus give the first-order correction to the quadratic action (5). We discuss the physical interpretation of the cubic terms in the next section whereas their explicit form and more details on the perturbative expansion are provided in Ref. [18].

Notice that there is an ambiguity in the definition of the mass eigenstates, connected to the freedom of performing field redefinitions. This issue is discussed in Ref. [10] and more details are provided in Ref. [18]. In particular, when defining the eigenstates $\delta G, \delta M$ in (6), we could in principle add terms nonlinear in $\delta g, \delta f$ (which would not change the physics). In this case the quadratic $\delta g, \delta f$ interactions would contain cubic interactions for $\delta G, \delta M$. In the following we fix this ambiguity by retaining the linear relations given in Eq. (6) and obtain the cubic interaction vertices whose coefficients are listed in Table I.

V. PHENOMENOLOGY

A. DM interactions

Let us discuss the effects of each kind of cubic vertex separately, identifying δM as our DM candidate.

The δG^3 terms are simply the usual gravitational self-interactions arising from the Einstein-Hilbert term of GR, whereas the self-interactions of the massive spin-2 field are given by the δM^3 terms. From Table I, it is clear that some of these vertices are enhanced in the limits of small α or large $m_{\rm FP}$, as compared to the δG^3 terms. Notice however that they are still suppressed by inverse powers of $m_{\rm Pl}$ when compared to SM self-interactions.

The $\delta G^2 \delta M$ terms describe the decay of the massive spin-2 field into two massless gravitons. While this decay would naively be allowed, we find that no such term is present and, therefore, DM does not decay into massless gravitons. The decay into SM fields is still allowed, although it is suppressed by the Planck mass of the matter coupling in Eq. (5) as we will discuss in more detail below. We would like to emphasize that, in our setup, the weakness of the interaction between DM and SM fields descends naturally from the very large value of the physical Planck

TABLE I. Coefficients of cubic interaction vertices (numerical factors neglected) in units of $m_{\rm Pl}^{-1}$. Vertices with a dimensionless coefficient are associated to two derivatives.

δG^3	$\delta G^2 \delta M$	$\delta G \delta M^2$	δM^3
$1, \Lambda$	0	$1, \Lambda, m_{\rm FP}^2$	$\alpha, \alpha\Lambda, \alpha m_{\rm FP}^2, \frac{1}{\alpha}, \frac{\Lambda}{\alpha}, \frac{m_{\rm FP}^2}{\alpha}$

mass $m_{\rm Pl}$: this is exactly what one expects if DM is a manifestation of gravity itself.

The $\delta G\delta M^2$ terms reveal that the DM field responds to the massless spin-2 field in the same way as standard baryonic matter. Consequently, the massive spin-2 field gravitates exactly as the postulated DM component of ΛCDM. Remarkably, this coupling is independent of α, and the feature persists in the GR limit of small α.

The last two points can also be understood by comparing the Noether and gravitational stress-energy tensors in our setup. The Noether stress energy is computed in the usual way from the quadratic theory, Eq. (5) which does not explicitly contain α, but only Λ and $m_{\rm FP}$. Furthermore, since the quadratic theory is diagonalized, there are no mixing terms $\delta G\delta M$ in the Noether stress energy. The gravitational stress energy, on the other hand, is obtained by varying the cubic interaction terms with respect to δG. It is known that these two definitions of stress-energy tensor coincide in flat space, i.e. for $\Lambda = 0$, after imposing the equations of motion; see e.g. [22]. This is consistent with the vertices displayed in the second and third column of Table I, which verify the independence of α as well as the absence of $\delta G^2\delta M$ terms. Of course, the agreement of the two stress-energy tensors can also be verified explicitly from the exact cubic vertices provided in [18]. It is also important to highlight that the equivalence between Noether and gravitational stress energy implies that in the nonrelativistic limit the massive spin-2 field acts as a dust source for the massless field.

B. DM decay and production

The universal interaction of spin-2 DM with the SM matter allows for its decay into species lighter than $m_{\rm FP}/2$, thereby providing possible signatures for indirect detection experiments. We estimate the associated decay width into a relativistic species X as [23]

$$\Gamma(\delta M \to XX) = \frac{C_X}{80\pi}\frac{\alpha^2 m_{\rm FP}^3}{m_{\rm Pl}^2} \tag{10}$$

where $C_X = \frac{1}{6}, \frac{1}{2}, 1$ for scalars, fermions and gauge bosons, respectively. The constraints on the individual decay widths are heavily dependent on the mass and the decay channels of the DM candidate [24]. The weakest upper bound on the mass $m_{\rm FP}$ comes from imposing that the decay width into SM particles is less than the inverse age of the Universe; this translates to the limit,

$$\alpha^{2/3} m_{\rm FP} \lesssim 0.1\ \text{GeV}. \tag{11}$$

The most conservative constraint from decay comes instead from Fermi-LAT bounds on the photon flux [2–4], which imply $\Gamma(\delta M \to \gamma\gamma) \lesssim 10^{-27}\ \text{s}^{-1}$. In this case, we obtain $\alpha^{2/3} m_{\rm FP} \lesssim 0.1$ MeV.

As for the possible production mechanisms, the weakness of the Planck-suppressed coupling means that the DM can be efficiently generated via standard out-of-equilibrium thermal production (freeze-in). In particular, our spin-2 DM can be produced via s-channel processes initiated by SM particles and mediated by the massless graviton. Assuming an averaged cross section times velocity of the typical order of $\langle\sigma v\rangle \approx m_{\rm Pl}^{-4} T^2$ at the temperature T, matching the observed DM abundance $\Omega_{\rm DM}$ via freeze-in means [25],

$$m_{\rm FP} \approx \frac{\Omega_{\rm DM} m_{\rm Pl}^3}{\Omega_{\rm b} T_*^3} m_{\rm p}\eta_{\rm b}, \tag{12}$$

where $m_{\rm p}$ is the proton mass, $\Omega_{\rm b}$ the abundance of baryons, $\eta_{\rm b}$ the baryon asymmetry and T_* the maximal reheating temperature. If we require that T_* does not exceed the inflation scale currently indicated by experiments, 10^{14} GeV, this implies TeV $\lesssim m_{\rm FP} \lesssim 10^{11}$ GeV. A feature of this production mechanism is its independence of the precise model for inflation. Since perturbativity requires $m_{\rm FP} < \alpha m_{\rm Pl}$, the stability bound Eq. (11) is satisfied only by masses up to $m_{\rm FP} \simeq 10^7$ GeV. These combined limits also imply that $\alpha \ll 1$, confirming the necessity for bimetric theory to be close to its GR limit.

C. Gravitational DM signatures

The most immediate prediction of our proposal is that DM will not be detected in current and future direct and collider searches, simply because its coupling to SM matter is by far too weak. Nonetheless, there are unique signatures which can attest our claim.

Self-interactions of our spin-2 DM are enhanced by inverse powers of α. In cluster collisions, baryonic and dark matter would then experience different drag forces possibly resulting in configurations like the one observed in the Abell 520 clusters. Currently, observation of Galaxy cluster mergers yield an upper bound on DM self-interactions of the order of $\sigma_{\rm DM}/m_{\rm DM} \lesssim 1$ barn/GeV [26], which however is poorly constraining. Finally, we remark that large DM self-interactions could result in differences between the baryonic and DM power spectra on small scales.

Another notable property of our DM candidate is that its gravitational interactions may differ from that of SM matter in curved spacetime. While in flat space the Noether and gravitational stress-energy tensors always coincide, the nonlinear mixing of the massive spin-2 field with the graviton could induce different behaviors in the presence of background curvature. This feature already manifests itself via a rather nontrivial presence of Λ in the $\delta G\delta M^2$ terms, c.f. Table I. Close to black holes or on cosmological scales, it could then be possible to detect modified gravitational interactions of DM.

Of course, our framework could be falsified by investigating additional signatures of bimetric theory which are not related to DM phenomenology. For instance, one possibility lies in observations of black holes. Indeed, since the standard no-hair theorem does not apply to bimetric theory, it is natural to expect that black holes, in general, possess hairs formed by the absorption of spin-2 DM particles. Another option is provided by the fact that the interaction term for the metrics $g_{\mu\nu}$ and $f_{\mu\nu}$ introduces corrections to Friedmann's equation which affect both expansion history and cosmological perturbation theory (see [27] for a summary). Depending on the values of α and m, i.e. on how close the theory is to GR, these effects can be observable as deviations from ΛCDM.

VI. CONCLUSIONS

We have identified an interesting DM candidate in the only known ghost-free extension of GR which includes a massive spin-2 field: the massive spin-2 particle is stable on cosmological scales and its interactions with SM fields are very weak. Remarkably, our DM particle possesses standard gravitational interactions in flat space and in parameter regions where bimetric theory passes all observational tests. In other words, bimetric theory resembles GR plus a gravitating DM particle, the origin of which is purely gravitational. The weakness of the interactions between DM and SM fields arises naturally from the weakness of gravitational interactions or, equivalently, from the large value of the physical Planck mass.

Observational signatures of our DM candidate range from indirect detection experiments (due to DM decay) to the observation of possible DM self-interactions in cosmic mergers. Assuming a thermal freeze-in DM production mediated by the massless graviton constrains the DM mass to the range TeV $\lesssim m_{\mathrm{FP}} \lesssim 10^7$ GeV. More stringent bounds are obtained in [18].

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