Planck mass charged gravitino dark matter

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Following up on our earlier work predicting fractionally charged supermassive gravitinos, we explain their potential relevance as novel candidates for dark matter and discuss possible signatures and ways to detect them.

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I. INTRODUCTION

In a very recent work [1] we raised the possibility that, very unconventionally, dark matter (DM) could consist at least in part of an extremely dilute gas of very massive stable gravitinos, which are furthermore fractionally charged and possibly strongly interacting. In this article we wish to further investigate this possibility, and to discuss possible observable signatures and ways to search for them. A scenario based on such large-mass DM candidates is obviously very different from conventional models where the masses of putative DM constituents usually range from fractions of an eV (for axion-like DM) to the TeV scale [for weakly interacting massive particle (WIMP)-like DM]]; for supersymmetric DM candidates there is a particularly large variety of mass ranges, owing to the large number of different models. With large mass a crucial issue is that of stability because superheavy particles participating in standard interactions can be expected to simply decay at a very early stage in the evolution of the Universe, unless a special mechanism is found that guarantees their survival to the present epoch. The crucial new ingredient ensuring stability here is the fractional charge of the DM candidates, together with their peculiar $SU(3)_c$ charge assignments, cf. Eq. (1) below. We note that integrally charged DM candidates have already been discussed in the literature [2]; likewise, and more exotically, DM candidates with very tiny (unquantized) charges have been considered [3,4]. However, the latter proposals all concerned sub-Planck mass particles.

Although perhaps not so well known, there is already a substantial literature on the possibility of DM consisting of superheavy particles (SHDM), which is now receiving renewed attention in light of the absence of low-energy supersymmetry at the LHC and failed WIMP searches. Early work in this direction includes Refs. [5–7] where the DM constituents were assumed to be subject to gravitational interactions only. Later work incorporated inflationary cosmology into the picture [8,9], for instance by studying the production of SHDM in the context of (large-field) inflationary models; for more recent work, see also Refs. [10–12] and references therein. A recurring feature of these studies is that the SHDM particles are still assumed to have only weak (or even superweak) interactions with SM matter, whence they are commonly referred to as "WIMPZILLAs." Since these considerations are mainly motivated by inflationary cosmology, the mass of the DM constituents, though very large, is usually still assumed to be well below the Planck scale, but instead on the order of the scale of inflation $\lesssim 10^{16}$ GeV [8–12]. By contrast, the present model combines the *Planck mass* with fractional electric charges and strong interactions of Standard Model (SM) type in a way that is completely new to the best of our knowledge [13], where, however, only the non-strongly-interacting gravitinos would contribute significantly to DM. This is a main distinctive feature that sets the present proposal apart from earlier work on SHDM.

Perhaps even more importantly, the present scenario is based on a fundamental ansatz that also aims for an explanation of the fermion content of the SM, and that draws its inspiration from the huge duality symmetry E_{10} that has been conjectured to underlie M-theory [14]. More specifically, and as explained in Ref. [1], our proposal relies on an attempt to embed the SM fermions into an M-theoretic framework extending $N = 8$ supergravity, which exploits the fact that after complete breaking of supersymmetry the remaining 48 spin-$\frac{1}{2}$ fermions of this theory can be put in precise correspondence with the 3×16 quarks and leptons of the SM (including right-chiral neutrinos), following an insight originally due to Ref. [15]; see also Ref. [16].

We stress that the present version of this proposal does *not* necessarily require supersymmetry, but rather relies on $K(E_{10})$, an infinite-dimensional extension of the usual R symmetries of extended supergravities, and on the fact that the degrees of freedom corresponding to a combination of eight massive gravitinos and 48 spin-$\frac{1}{2}$ fermions at a given spatial point (obtained after appropriate decomposition of the $D = 11$ gravitino components) constitute an irreducible unfaithful spinorial representation of $K(E_{10})$ [17,18]. The unusual feature here is that—in contradistinction to accepted model-building wisdom (as e.g., for GUT-type scenarios)—the symmetry can be so enormously enlarged *without* increasing the size of the fermion multiplet. This interpretation hinges crucially on the assumption of *emergent* spacetime in Ref. [14] as there appears to be no way to achieve this in the framework of space-time-based quantum field theory.

Apart from the intrinsic interest of incorporating infinite-dimensional duality symmetries into unification in entirely novel ways, the main motivation for our proposal comes from the fact that, as far as the fermionic sector is concerned, it can make do with the particle content of the SM, that is, the observed three generations of quarks and leptons (including right-chiral neutrinos). This is in accord with indications from the LHC that there may not be much in terms of new physics beyond the electroweak scale, and increasing evidence that the SM might survive up to the Planck scale more or less *as is*, contrary to numerous still popular scenarios postulating a plethora of new particles at the TeV scale or just beyond. The possibility that the present framework also offers new options for DM is an extra incentive for further study.

II. MAIN NEW FEATURES

Our proposal implies a number of highly unusual features for the DM gravitinos. We caution readers that these features rely on a number of assumptions that are contingent on the proposal of Ref. [14] according to which the full conjectured E_{10} symmetry and its compact subgroup $K(E_{10})$ manifest themselves only in a "near singularity limit" where space-time is assumed to de-emerge. With this reservation in mind let us list the special properties:

(1) All gravitinos are assumed to be extremely massive with masses $m \sim M_{\rm Pl}$, or not too far from this scale. This high mass value is a consequence of the assumption that supersymmetry—if at all present—is broken already at the Planck scale, leaving no room for low-energy supersymmetry (with a single Majorana gravitino which would manifest itself in completely different ways). In fact, as we already emphasized in Ref. [1], supersymmetry might actually never be realized at *any* energy as a *bona fide* symmetry in the framework of space-time-based quantum field theory.

(2) The eight massive gravitinos split as

$$\left(\mathbf{3},\frac{1}{3}\right) \oplus \left(\bar{\mathbf{3}},-\frac{1}{3}\right) \oplus \left(\mathbf{1},\frac{2}{3}\right) \oplus \left(\mathbf{1},-\frac{2}{3}\right) \tag{1}$$

under $SU(3) \times U(1)$. Identifying this SU(3) with $SU(3)_c$ as in Ref. [1], a complex triplet of gravitinos would thus be subject to strong interactions [the alternative option of identifying SU(3) with the family symmetry $SU(3)_f$ is disfavored for the reasons given in Ref. [1]]. Furthermore, as explained in Ref. [19], the U(1) in Eq. (1) is identified with $U(1)_{em}$ whence all gravitinos carry *fractional electric charges*. As we will see, the $SU(3)_c$ assignments in Eq. (1) lead to distinct and well-separated physical consequences: while the color singlets would mainly contribute to DM, the strongly interacting color triplet gravitinos could play a key role in explaining ultrahigh-energy cosmic rays (UHECRs) [20].

(3) Despite their strong and electromagnetic interactions with ordinary matter, the Planck-mass gravitinos would be stable. This is due to their fractional charges since there are simply no (confined or unconfined) fractionally charged final states in the SM into which they could decay in a way compatible with $SU(3)_c \times U(1)_{em}$. Being stable all these particles should be around us, though in extremely low abundance since the only processes that change the gravitino number are annihilations of gravitinos with antigravitinos and these are expected to be extremely rare over the whole history of the Universe after the Planck era; see below.

(4) The color-nonsinglet gravitinos should form bound states with quarks so as to avoid colored final states for temperatures $T < \Lambda_{\rm QCD}$. Importantly, since colored and anticolored gravitinos have electromagnetic charge $+\frac{1}{3}$ and $-\frac{1}{3}$, respectively, with the known $SU(3)_c$ assignments of the SM quarks there is no way to combine gravitinos with quarks or antiquarks to build color-singlet states that are neutral or integrally charged. Of course, an important open question here concerns the strong interaction dynamics of these superheavy "meso-gravitinos" or "baryo-gravitinos." We here appeal to heavy quark theory (see e.g., Ref. [21]), where the confinement scale is set by the difference between the mass of the bound-state meson and the mass of the heavier constituent, which is usually of the order of $\Lambda_{\rm QCD}$.

(5) Independently of whether they are in bound states or not, the gravitinos do not interact in any way with the cosmic microwave background (CMB) despite their electric charges. This follows immediately from the Thomson formula, according to which the total cross section (for low-energy photons) is

proportional to the square of the Compton wavelength of the scatterer (see e.g., Ref. [22]). In our case, the relevant scale is the Planck length, and hence the cross section is suppressed by a huge factor, and thus completely negligible.

(6) By contrast, interactions with charged non-strongly-interacting matter are governed by the Rutherford formula, and therefore are much like ordinary charged particle interactions. Being essentially at rest with respect to the cosmic frame (see below) the gravitinos would merely "stir" the surrounding charged light matter particles but not affect their thermalization. Unlike common DM candidates with masses $\lesssim\mathcal{O}(1\ \mathrm{TeV})$ they would thus not produce any significant dissipative effects in the evolution of the Universe, except possibly in the very earliest moments after the Planck era.

(7) The color-singlet gravitinos in Eq. (1) (which do not participate in strong interactions) are never in thermal equilibrium during the evolution of the Universe after the Planck era, so common astrophysical wisdom (see e.g., Refs. [23,24]) does not apply. This can be seen as follows. The inverse collision time is given by the standard formula $\Gamma\sim\langle n\sigma v\rangle$ where n is the particle number density and σ is the annihilation cross section. For the annihilation of a charged gravitino-antigravitino pair of mass M and charge e into a pair of spin-$\frac{1}{2}$ fermions the cross section behaves as $\sigma v\propto\alpha^2/M^2$, where v is the velocity of the incoming particles (which is small) and $\alpha\equiv\alpha(M)=e(M)^2/4\pi$. Thermal equilibrium requires $\Gamma\gtrsim H\sim T^2/M_{\mathrm{Pl}}$ [23], so with the general formula $n=g(\mu T/(2\pi))^{3/2}e^{-\mu/T}$ for particles of mass μ ($g=4$ for each massive gravitino species) this constraint translates into an approximate condition

$$\left(\frac{\mu}{T}\right)^{\frac{1}{2}}e^{-\mu/T}\gtrsim\frac{\mu}{\alpha(\mu)^2M_{\mathrm{Pl}}}\qquad(2)$$

which for $\mu\sim M_{\mathrm{Pl}}$ and $T<M_{\mathrm{Pl}}$ can never be satisfied [note that $\alpha(\mu)\lesssim O(0.1)$ for all SM gauge couplings over the whole range of μ from the weak scale up to M_{Pl}]. In other words, the non-strongly-interacting Planck-mass DM gravitinos would be frozen out from the very beginning. Their abundance thus cannot be estimated from thermal equilibrium but requires a "pre-Planckian" explanation. The rapid decrease of the annihilation cross section $\propto M_{\mathrm{Pl}}^{-2}$ of color-singlet gravitinos, together with their extreme dilution, also shows that they have no effect on the CMB or UHECR processes.

(8) By contrast, the strongly interacting (color-triplet) gravitinos can reach thermal equilibrium, due to their strong interactions and the fact that the relevant cross section does *not* decrease with energy [25], unlike for the color-singlet gravitinos, thus allowing for an estimate of the color-triplet gravitino density. This density turns out to be too small for the strongly interacting gravitinos to contribute in any significant way to DM, unlike the color-singlet gravitinos. However, they could play a key role in explaining UHECR events [20].

(9) If any signals originating from DM gravitinos were to be found they would provide direct access to Planck-scale physics. We also note that for a Planck-mass particle the Compton wavelength coincides with the Schwarzschild radius (both are thus nearly equal to the Planck length). When viewed as mini black holes our gravitinos are very close to, but strictly below extremality (because $\frac{2}{3}<1$!). As a result the attractive force for oppositely charged gravitinos is almost doubled, while for charges of the same sign we are very close to a "force-free" Bogomol'nyi-Prasad-Sommerfield-type situation. Possible consequences of this fact for cosmological issues (such as structure formation) remain to be explored, however.

Let us emphasize that the present scenario is completely different from earlier proposals with *light* neutral (Majorana) gravitinos as DM candidates. In conventional scenarios of low-energy supersymmetry and supergravity, gravitinos do *not* carry SM charges (this would require N-extended supergravities with at least $N\geq 2$, but for these one cannot have chiral gauge interactions with noncomposite gauge bosons). Depending on their mass, such neutral gravitinos would either decay into lighter supersymmetric particles (neutralinos) via the Noether interaction present in any supergravity Lagrangian, or themselves contribute to DM if they cannot decay. Either of these scenarios differs from the present one since our gravitino DM candidates *do* participate in SM interactions, but cannot decay because of the absence of suitable fractionally charged final states in the SM, despite their interactions with SM matter. So it is precisely the exotic gravitino charge assignments that can make our Planck-mass gravitinos survive to the present epoch.

III. SOME PROPERTIES OF SUPERHEAVY GRAVITINO DARK MATTER

As we said, the possibility of DM carrying SM charges [2] has already been considered in the literature, although not very prominently because DM is usually assumed to interact only very weakly with SM matter, apart from their gravitational interactions [23]. The relevant analyses are obviously very model dependent (see e.g., Ref. [2]), and usually apply only for much lighter DM constituents, so accepted cosmological bounds may be invalid for the case of masses of the order of M_{Pl} considered here. In fact, at least in more conventional DM scenarios, electrically charged DM is already very strongly constrained by existing data: it is either completely diluted, or otherwise the electric charges of putative DM particles must be extremely small. Indeed, the most stringent cosmological bound on the charge of DM particles of mass m is [26–28]

$$|q| \lesssim 7.6 \times 10^{-10} \left(\frac{m}{1\ \mathrm{TeV}}\right)^{\frac{1}{2}} \tag{3}$$

within the 90% confidence limit. For the DM candidates usually discussed (axion-like or WIMP-like, or any kind of new particle associated with low-energy supersymmetry) which are assumed to have masses $\lesssim \mathcal{O}(1\ \mathrm{TeV})$ this implies that the allowed charges are $\lesssim \mathcal{O}(10^{-10})$. This completely excludes charged DM of any conventional type. [A possible way out here would be to invoke new U(1) gauge interactions but there is neither observational evidence nor any compelling theoretical reason for them.] Remarkably, however, if we assume that the DM particle has a Planck-scale mass, then the admissible charge comes out to be of order unity: for $m \sim 10^{19}$ GeV the above formula gives

$$|q| \lesssim 7.6 \times 10^{-2}. \tag{4}$$

Taking into account the theoretical uncertainties and model dependencies, this value is quite compatible with charges of order one!

The assumed large mass of the DM gravitinos has another important consequence: it is a well-known result in general relativity that in the course of the expansion of the Universe any peculiar motion with respect to the cosmic frame of a massive particle out of equilibrium decreases as the inverse of the scale factor. So whatever the initial velocity distribution was shortly after the Planck era, it is reduced by a factor of $a_{\mathrm{PL}}/a_{\mathrm{now}} \sim 10^{-30}$, despite occasional scatterings with particles that will not appreciably change the energy because of the large mass. In other words, the superheavy gravitinos would be effectively at rest with respect to the CMB rest frame, with a very small velocity dispersion. However, the situation changes when structures are formed: then the heavy gravitinos can be trapped by a galaxy and subsequently move along geodesics, with a velocity of the order of several hundred km/s relative to the CMB (i.e., the escape velocity of the Milky Way galaxy at a typical distance from the center). Not much appears to be known about the motion of trapped DM *relative to* luminous matter inside galaxies, but it seems reasonable to assume that it simply "moves along" with luminous matter, with a small velocity dispersion.

In conclusion we would expect our DM candidates to move with an effective velocity of some tens of kilometers per second with respect to Earth (this follows also from simple considerations based on the virial theorem in Newtonian physics). In this case their nonrelativistic kinetic energy is of order

$$E \sim \frac{1}{2} M_{\mathrm{Pl}} v^2 \sim 10^{20}\ \mathrm{eV}. \tag{5}$$

To estimate their penetration depth we recall that a proton of velocity 400 km/s (i.e., with kinetic energy ~1 keV) in iron loses approximately 300 MeV per centimeter [29]. Being subject to similar electromagnetic interactions this implies a roughly 10 times smaller energy loss rate for our DM candidates (because of the charge squared factor $\frac{4}{9}$ or $\frac{1}{9}$), so their range would be

$$R \sim \frac{E}{30\ \mathrm{MeV/cm}} \sim 3 \times 10^{10}\ \mathrm{m}. \tag{6}$$

Consequently, these particles will easily pass through the Earth without appreciable change in energy. Nevertheless, because of their electromagnetic interactions they will uniformly ionize their surroundings, leaving a straight ionized track all along their path. This track would have a lateral extension of a few nanometers, and would thus not be visible in ordinary light. By contrast, the passage through the Sun or some other star might lead to some absorption, due to the much larger stopping power of a plasma environment. But even assuming that all gravitinos hitting the Sun were stopped, and taking into account their low abundance and flux rates (see below), the total amount of gravitino DM captured inside the Sun would be rather tiny and therefore not affect stellar processes in any significant way (neutron star evolution also allows for Planck-mass DM since known bounds only exclude masses $< 10^{16}$ GeV [30]).

To estimate the flux, we recall that the mass density of DM in our galaxy in the proximity of the Solar System is usually given as [31]

$$\rho_{\mathrm{DM}} \sim 0.3 \times 10^6\ \mathrm{GeV \cdot m^{-3}}. \tag{7}$$

If DM is made out of Planck-mass particles, this means roughly 3×10^{-14} particles per cubic meter, that is, a very low abundance to compensate for the very large DM constituent mass. Putting in an estimated average velocity $\beta \sim 10^{-4}$ (that is, on the order of the Earth's orbital velocity around the Sun) we arrive at a flux estimate of

$$\Phi \lesssim 10^{-14}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}} \sim 0.003\ \mathrm{m^{-2}\,yr^{-1}\,sr^{-1}}. \tag{8}$$

We stress that apart from uncertainties about the velocity distribution, there are also uncertainties about the assumed DM density in our vicinity which could be subject to potentially large local variations; the comparison of this value with the experimental bounds may provide a hint on the scale of these variations.

IV. PROSPECTS FOR DETECTION

What are the prospects for actually detecting such nonrelativistic superheavy DM candidates? Searches for ionized tracks coming from DM particles have a long history; see e.g., Ref. [32] and references therein. Currently there are several direct WIMP searches (see e.g., Refs. [32,33]), as well as accelerator experiments (for example MoEDAL at CERN [34]). Alternatively one might consider an underground *paleo-detector* that could identify long ionized tracks preserved in rock, and discriminate them from muon tracks or neutrino induced events. In fact, there are projects to detect tracks in old rocks [35] and plans for experiments to look for superheavy DM with multiple scatterings [36]. There are also limits on the allowed fluxes for fractionally charged superheavy DM [37], but these concern only *ultrarelativistic* particles ($\beta > 0.25$).

Nevertheless, it appears that WIMP-like searches of the type currently pursued are unsuitable for detecting superheavy gravitinos. For the existing experiments LUX [38], XENON1T [39] and DAMA/LIBRA [40], the flux (8) is way too low to be seen, as their fiducial volumes/fiducial areas are simply too small for a detection. For instance, the LUX experiment had 250 kg of liquid Xenon [with density $2.9\ \mathrm{g/cm^3}$ it gives a box of effective volume $(44\ \mathrm{cm})^3$] and was effectively operating for $95 + 332$ days. With the estimated flux (8) this would give a total of $0.003 \times 4\pi \times 0.44 \times 0.44 \times 427/365 \sim 0.009$ hits over the whole time of exposure; the estimates for XENON 1T are similar. DAMA/LIBRA had a comparable fiducial area but a much longer exposure; however, it looked only for single hit events very different from our putative gravitino tracks. Likewise large detectors used in accelerator experiments have the triggering procedures focused only on relativistic particles (as for CMS, ATLAS or Super-Kamiokande).

Much more relevant to the present proposal are past searches for magnetic monopoles with very large fiducial areas/volumes that were conducted up until 2000, and that have already established significant limits; see Ref. [41] for an early review, and the MACRO report [42] for a final summary (though magnetic monopoles were never considered to be serious candidates for explaining DM). Indeed, GUT-mass magnetic monopoles would produce signals very similar to the ones postulated here (although the degree of ionization caused by monopoles might be somewhat different). However, because of their large magnetic charge their velocity dispersion is expected to be much larger than in our case, as magnetic monopoles can be accelerated to relativistic speeds by galactic magnetic fields. It was presumably for this reason that past searches were limited to velocities in the range $10^{-4} < \beta < 1$ [41]. By contrast, we expect gravitinos to have velocities of the order of $\beta \sim 10^{-4}$, and then gravitino-induced signatures would have no natural background (except possibly extremely heavy magnetic monopoles). Hence the cleanest way to search for superheavy charged gravitinos seems to be a dedicated time-of-flight underground experiment looking for *slow* ionizing particles. This could be done for instance by resuscitating and/or redesigning the old experiments to cover the so-far little explored velocity range $10^{-5} < \beta < 10^{-4}$ aiming at lower fluxes than previously considered [43].

One may note that from the present perspective the negative results of MACRO [42] could also be interpreted as evidence for a significantly lower DM density in the vicinity of the Earth than the usually quoted average value of $0.3\ \mathrm{GeV \cdot cm^{-3}}$. The comparison of the expected flux given in Eq. (8) with the MACRO bound [42] for velocities $\beta = 10^{-4}$ and fluxes $\Phi \sim 3 \times 10^{-16}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ could be a hint that the actual value of the local DM density may be significantly lower than the usually assumed value (7). Indeed, in Ref. [20] we have put forward the hypothesis that a large fraction of the DM in galaxies could reside inside stars, thereby depleting the DM content of interplanetary space. In that case the only remaining option for detecting DM might be a paleo-detector with a very long exposure time, similar to Ref. [35].

We finally note that, while posing a considerable challenge, experiments searching for exotic DM candidates with properties and fluxes similar to the ones predicted by the present scheme are of interest in their own right, independently of the theoretical motivation given here.

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