Superheavy Gravitinos and Ultra-High Energy Cosmic Rays

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Dedicated to the memory of Murray Gell-Mann

We argue that the superheavy gravitinos that we had previously proposed as candidates for Dark Matter can offer a possible explanation for the ultra-high energy cosmic ray (UHECR) events observed at the Pierre Auger Observatory, via gravitino anti-gravitino annihilation in the 'skin' of neutron stars. The large mass and strong interactions of these particles, together with their stability against decays into standard matter are essential for the proposed explanation to work. In particular, it ensues that UHECR events can be understood to originate from neutron stars inside a GKZ horizon of ~ 50 Mpc. The composition of neutron stars near their surface could play a crucial role in explaining the presence of heavy ions in these events. If confirmed, the present results can be taken as evidence for the fundamental ansatz towards unification on which they are based.

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To date there does not appear to exist a fully satisfactory explanation in terms of known physics for the ultra-high energy cosmic ray (UHECR) events observed over many years at the Pierre Auger Observatory [1–3], which reach maximum energies of $E \gtrsim 10^{19}$ eV saturating the GKZ bound [4]. A particularly puzzling feature is the occurrence of not just protons, but heavier ions (He, N, Fe, *etc.*) which appear to dominate towards the very highest energies [1]. The absence of a compelling scenario may indicate the need for new physics beyond the Standard Model (SM). In this Letter we present a possible new explanation very different from previous proposals. This is based on our previous work [5, 6] where we have raised the possibility that 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 strongly interacting. As we will argue here these can in principle furnish a fairly simple explanation for the most energetic cosmic ray energy events, both qualitatively and quantitatively.

Possible acceleration mechanisms relying on more conventional physics, such as Fermi acceleration of known particles by shock waves, have been amply discussed in the literature [3], but so far no clear picture has emerged. A more exotic possibility is to invoke the Penrose process of extracting energy from a rapidly rotating Kerr black hole [7]. Unfortunately, such an explanation runs into difficulties with Thorne's theorem [8], according to which rapidly spinning black holes obey $a/M \lesssim \beta_{max} = 0.998$ (where a is the usual rotation parameter of the Kerr solution). It seems reasonable to assume that this bound also sets an upper limit for the velocity that a proton (or any other elementary particle) can acquire in such a process, but then the maximum attainable energy falls far short of the required $E \gtrsim 10^{19}$ eV (corresponding to $1 - \beta \sim 10^{-20}$). Another possible explanation could be via annihiliation of GUT-like objects, such as GUT mass magnetic monopoles. However, even assuming these do exist, it is not clear whether and how they could accumulate in sufficient amounts to explain the observed event rates. The same objection applies to other hypothetical GUT-like objects like leptoquarks or heavy gauge bosons, as these would most likely have decayed already long ago. In conclusion, there appears to be no compelling mechanism, neither from relativistic astrophysics nor from SM physics or widely discussed "Beyond the SM" scenarios, that could plausibly explain the acceleration of known (or suspected new) particles to the required energies, nor account for the observed abundance of heavy ions.

The new explanation offered in this Letter is entirely different, being based on a more fundamental ansatz [5, 6]. That work was originally motivated by an attempt to explain the fermion content of the SM, with three generations of 16 quarks and leptons each, from the spin-$\frac{1}{2}$ fermion content of maximal $N=8$ supergravity, following a proposal orginally due to Gell-Mann [9, 10]. This proposal was further developed in [5, 12, 13] in order to fully account for the $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_w \times \mathrm{U}(1)_{em}$ assignments of the SM fermions, by exploiting properties of the maximal compact subgroup ('R symmetry') $K(E_{10})$ of the conjectured maximal duality symmetry E_{10}. Just like $N = 8$ supersymmetry, this group theoretical framework entails the existence of eight massive gravitinos in addition to the 48 fundamental spin-$\frac{1}{2}$ fermions. The present proposal is thus not simply based on *ad hoc* postulates, but part of a wider framework for unification with emergent space-time [11]; however, (Planck scale) supersymmetry is here not necessarily realized as a *bona fide* symmetry in the framework of space-time based quantum field theory. Although it so far relies solely on group theoretic considerations (whereas a proper dynamical description would require a much better understanding of the infinite-dimensional duality symmetries underlying it), one can nevertheless derive some interesting consequences from this kinematic framework even without detailed knowledge of the dynamics.

The eight massive gravitinos are characterized by the following properties. (i) From the group theoretic analysis given in [12, 13] it follows that they transform as

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

under $\mathrm{SU}(3)_c\times\mathrm{U}(1)_{em}$ [19]. Hence, unlike DM candidates usually considered (such as axions or WIMPs), these particles *do* participate in strong and electromagnetic interactions, with coupling strengths of order $\mathcal{O}(1)$. (*ii*) All gravitinos are assumed to be supermassive with masses not too far from the (reduced) Planck mass $M_{\rm PL}\sim 2\cdot 10^{18}\,\mathrm{GeV/c^2}\sim 4\cdot 10^{-9}$kg (in a supersymmetric context this would correspond to Planck scale breaking of supersymmetry). (*iii*) The charge assignments (1) ensure that, despite their strong and electromagnetic interactions with ordinary matter, the superheavy gravitinos are stable because there are no (confined or unconfined) fractionally charged final states in the SM into which they could decay in a way compatible with $\mathrm{SU}(3)_c\times\mathrm{U}(1)_{em}$ and (1). Hence the only process that can lead to their disappearance is mutual annihilation, and this will be the crucial effect considered here. As we will see, however, there will appear an essential difference between the two kinds of gravitinos in (1), in that only the strongly interacting gravitinos will contribute significantly to the annihiliation processes producing UHECR events.

Both the large gravitino mass and the amount of accumulated mass of these particles, which is on the order of the combined DM mass in the Universe, are necessary to understand the large energies and the rates of the observed UHECR events, as we shall now explain. In addition we need to make one important further assumption concerning the *local* distribution of DM in stellar systems. The average density of DM within a typical galaxy is commonly given as $\rho_{DM}\sim 0.3\times 10^6\ \mathrm{GeV\cdot m^{-3}}$ (corresponding to one proton per cubic centimeter) [14]. Extrapolating this number to Planck mass particles we would get $\sim 10^{-13}$ gravitinos per cubic meter [20], hence an extremely dilute gas of DM particles. Most of these will be color singlet gravitinos, whereas the strongly interacting non-singlets make up only a small fraction of these, see below. Now in [6], we have already raised the possibility that DM, while more or less uniformly distributed in interstellar space, might be subject to larger *local* variations near stars. This could happen if the DM co-rotates with the stars around the center of the galaxy, but not relative to them, unlike the dust that gives rise to planets and ends up rotating around (and not being absorbed by) the star. Then, a typical star could eat up much of the surrounding DM in its vicinity over its lifetime, depleting a ball of diameter of a few lightyears around it. For a pre-supernova star and a volume of (two lightyears)$^3\sim 10^{49}\,\mathrm{m}^3$ this would yield a total amount of DM *within* the star of $\lesssim 10^{27}$ kg, corresponding to a fraction of $\lesssim 10^{-3}$ of its total mass. Although seemingly non-negligible it corresponds to only one gravitino per 10^{22} protons or helium nuclei. This number is far too small to affect standard stellar processes in any significant way, especially since our gravitinos cannot decay into SM particles. As participants in the strong interactions, they would nevertheless be in thermal equilibrium, with a very small velocity dispersion of $(\Delta v)^2\sim kT/M_{\rm PL}$. In contradistinction to luminous matter (for which Δv is very large), they would thus continue to slowly migrate towards the center of the star, especially if the latter develops a core of heavier nuclei, thereby avoiding the usual problem of 'missing the center' [15].

At this stage the gravitino density is still so small that annihilation processes can be neglected. Furthermore, because the color singlet gravitinos in (1) interact only electromagnetically their annihilation cross section is proportional to the inverse mass squared ($\sigma v\sim (\pi\alpha^2\hbar^2/(4M^2c)$ for small initial velocities) [21]. The situation is entirely different for the strongly interacting gravitinos corresponding to the two color triplets in (1); as they are mainly responsible for the effect to be discussed here we will henceforth restrict attention to them only. For strongly interacting particles the annihilation cross section σ varies only very slowly with the energy $\sqrt{s}$, and can be approximated by the formula [16]

$$\langle\sigma\beta\rangle\ \sim\ \left[36-4\ln\left(\frac{\sqrt{s}}{\Lambda_{QCD}}\right)+0.84\left(\ln\left(\frac{\sqrt{s}}{\Lambda_{QCD}}\right)\right)^2\right]\mathrm{mb} \quad (2)$$

with $\Lambda_{QCD}=0.4$ GeV. This formula is non-perturbative in the sense that it does not rely on a perturbative calculation, but is based on fitting a general ansatz consistent with the Froissart bound with experimental data [16]. Putting $\sqrt{s}=2\gamma m_p$ and $\gamma\sim 1$ we find $\langle\sigma\beta\rangle\sim 32$mb, a value that we will use below (1 mb $\sim 10^{-31}\mathrm{m}^2\sim 2.5\ \mathrm{GeV}^{-2}$).

To estimate the present density ρ_0 of strongly interacting (color triplet) gravitinos, we observe that with a gravitino mass close to $M_{\rm PL}$, the usual requirement of thermal equilibrium reads

$$\Gamma=\rho\langle\sigma v\rangle\ >\ H=\frac{\pi(k_BT)^2}{3\sqrt{5}\hbar c^2M_{\rm PL}} \quad (3)$$

Adopting from now on the usual unit conventions $\hbar=c=k_B=1$ (hence $2\cdot 10^{-7}\,\mathrm{eV}\cdot\mathrm{m}=1$), this translates into an equation for the relic abundance ρ_T

$$(32\,\mathrm{mb})\,\rho_T\equiv(32\,\mathrm{mb})\,g\left(\frac{mT}{2\pi}\right)^{3/2}\mathrm{e}^{-m/T}=\frac{T^2}{2M_{\rm PL}} \quad (4)$$

($g=4$ for a massive gravitino), or

$$\frac{m}{T}\sim 90\quad\Rightarrow\quad\rho_T\sim 3\cdot 10^{59}\,\mathrm{m}^{-3} \quad (5)$$

The temperature $T\sim 2\cdot 10^{16}$ GeV corresponds to cosmic time $t_T=M_{\rm PL}/T^2\sim 3\cdot 10^{-39}$ s. The *present* density ρ_0 is obtained from ρ_T by the well known formula

$$\rho_0=\rho_T\left(\frac{a_T}{a_0}\right)^3 \quad (6)$$

(since superheavy gravitinos are non-relativistic). Taking the end of the radiation dominated era as 10^{12} s we get

$$\frac{a_T}{a_0}=\left(\frac{3\cdot 10^{-39}}{10^{12}}\right)^{1/2}\left(\frac{10^{12}}{3\cdot 10^{17}}\right)^{2/3}\sim 10^{-29} \quad (7)$$

where the two factors correspond to the radiation dominated and matter dominated eras, respectively. Thus

$$\rho_0 \sim 5 \cdot 10^{-28} \text{ m}^{-3} \quad \left(\sim 10^{-9} \text{ GeV} \cdot \text{m}^{-3} \right) \qquad (8)$$

Assuming now (as before) that the star 'swallows' all gravitinos within a radius of two lightyears we get for the total number of color triplet gravitinos inside the star

$$N_g \sim 2 \cdot 10^{22} \qquad (9)$$

As we argued above, the gravitinos inside the star are in thermal, but not mechanical equilibrium, so for a pre-supernova star we expect them to cluster more towards the iron core (where no nuclear reactions take place anymore). As already pointed out, the number (9) is too small to produce any significant effects in the star – even in the iron core the lifetime of a gravitino still exceeds the lifetime of the Universe, see below.

The situation changes dramatically if the star collapses to a neutron star. In that case, as explained above, most of the gravitinos will be contained in its iron core even prior to the supernova collapse, and the gravitinos will collapse with the core due to the sudden increase of gravititional pull towards the center. As a consequence, they will get squeezed into a ball of radius $\mathcal{O}(10\,\text{km})$ [17], and their density increases to

$$\rho_{NS} \sim 5 \cdot 10^9 \,\text{m}^{-3}. \qquad (10)$$

This 'compactification' is absolutely crucial since the gravitinos need to be packed sufficiently closely to enable them to annihilate in any appreciable rate. The inverse lifetime of the gravitino as a function of the neutron star time from its birth is

$$\Gamma_{NS}(t) = \rho_{NS} \exp\left(-\int_0^t \Gamma_{NS}(t')\text{d}t' \right) \langle \sigma v \rangle \qquad (11)$$

which gives

$$\Gamma_{NS}(t) = \frac{\Gamma_{NS}(0)}{1 + \Gamma_{NS}(0)t} \qquad (12)$$

with the initial value (and $\langle \sigma\beta \rangle \sim 32\text{mb}$)

$$\Gamma_{NS}(0) \sim \left(5 \cdot 10^9\right) \cdot \left(32 \cdot 10^{-31}\right) \cdot \left(3 \cdot 10^8\right)\text{s}^{-1} \sim 5 \cdot 10^{-12}\text{s}^{-1} \qquad (13)$$

Therefore the actual annihilation rate depends on the age of the neutron star. We also see that before the collapse for a pre-supernova star with an iron core of $\mathcal{O}(1000\,\text{km})$ diameter the rate would be lower by a factor of $\sim 10^{-12}$.

Having derived the approximate annihilation rate inside the neutron stars we can now estimate the number of UHECR particles coming from the annihilation. Because the superheavy gravitinos interact strongly, each single annihilation will result in a violent burst of Planck scale energy, producing a multitude of (mostly hadronic) particles. We can roughly estimate their multiplicity by extrapolating to Planckian energies the formula [18]

$$\text{multiplicity} \sim 0.27\, \alpha_s(\Lambda) \exp\left(\frac{2.26}{\sqrt{\alpha_s(\Lambda)}} \right) \qquad (14)$$

Here the strong coupling α_s is to be evaluated at $\Lambda \sim 0.35\sqrt{s}$. Plugging in $\sqrt{s} \sim M_{\text{PL}}$ gives $\mathcal{O}(10^6)$ particles per annihilation [22]. The total energy $\sim M_{\text{PL}}$ will be distributed over all these particles, with an average energy of 10^{13} GeV $\sim 10^{22}$ eV per particle. This happens to be of the same order of magnitude as the maximum energy observed in high energy cosmic rays! Nevertheless, because of their strong interactions and the large density inside the neutron star the annihilation products cannot escape because they will either lose too much energy or be stopped altogether on their way out from the core of the neutron star. For this reason, we expect the main contribution to UHECR particles to come from the outermost shell of the neutron star of width $d \lesssim \mathcal{O}(100\,\text{m})$ *i.e.* $\sim 3\%$ of the volume. There the density drops down by a factor 10^{-5} relative to the core density [17], and is given by $\sim 10^{13}$ kg m^{-3} such that $\rho(R - d) = 10^{40}$ m^{-3}. (The width d is here determined by the requirement that the number of collisions times the loss of energy per collision, here assumed to be $\sim \mathcal{O}(1\text{GeV})$, should be much lower than the total energy of the proton of 10^{12} GeV, which gives $\rho(R - d)\sigma d < 10^{12}$, where $\sigma \sim 10^{-30}$ m^2).

Importantly, this outer shell is thought to be rich in heavier nuclei, and also iron nuclei [17], so the high energy particles that can escape will 'sweep up' not just neutrons and hadrons, but also heavier ions before exiting the neutron star. Independently of subtleties of strong interaction dynamics the 'proto-nuclei' generated in this process will subsequently decay to stable isotopes, and Fe nuclei in particular, and thus end up as ultra-high energy stable ions of the type observed by [1].

Due to various uncertainties, however, it is not possible to give more precise estimates at this point. For instance, the density of gravitinos near the skin may actually be enhanced by a 'centrifuge effect' for rapidly spinning neutron stars. For this reason we shall simply take the value (10) to hold also near the skin of the neutron star, and assume that 3% of the neutron star volume is effectively available for this process. A young neutron star would thus continuously 'spray' high energy protons or heavy ions at a rate

$$\sim 6 \cdot 0.03 \cdot (2 \cdot 10^{22}) \cdot (5 \cdot 10^{-12}) \cdot 10^6\text{s}^{-1} \sim 2 \cdot 10^{16}\text{s}^{-1} \qquad (15)$$

from its surface into outer space (the factor of 6 comes from the number of the strongly interacting gravitino species). To calculate how many of these will eventually reach Earth, we recall that, with an estimated average number of neutron stars per galaxy of $\sim 10^8$ and $\sim 10^7$ galaxies within a GKZ horizon of 50 Mpc [3], we have a total number of 10^{15} UHECR emitters. Denoting the density of neutron stars in the universe by $\rho_N(\mathbf{x})$ (where $\mathbf{x} = 0$ corresponds to the position of Earth), the total rate arriving at Earth is thus

$$N_E \sim \left(2 \cdot 10^{16} s^{-1}\right) \times \int \frac{\rho_N(\mathbf{x}) d^3x}{4\pi|\mathbf{x}|^2} \qquad (16)$$

For a rough estimate of the total flux we neglect density variations, taking $\rho_N = \text{const}$, in which case the integral is easily evaluated to be

$$N_E \sim \rho_N R_{max} \times 2 \cdot 10^{16} \mathrm{s}^{-1} \quad (17)$$

Putting $R_{max} \sim 50\,\mathrm{Mpc}$ as a cutoff we arrive at the flux of UHECR arriving on Earth as

$$N_E \sim \frac{10^{15} \cdot 2 \cdot 10^{16}}{4(10^{24})^2}\ \mathrm{m}^{-2}\mathrm{s}^{-1} \sim 5 \cdot 10^{-18}\ \mathrm{m}^{-2}\mathrm{s}^{-1} \quad (18)$$

which is not too far off the observed rate of one UHECR event per month and per 3000 km^2 [1]. To be sure, the UHECR emitters are not evenly distributed throughout the universe, and we therefore expect an increased number of events to originate from superclusters of galaxies rich in neutron stars (the supergalactic plane, in particular, as also suggested by the data [1]). In particular the integral in (16) may receive its dominant contribution from a disk rather than the full ball. We also note that with a maximum available energy of $\mathcal{O}(10^{22}\,\mathrm{eV})$ our proposal can also explain the existence of (very rare) UHECR events *exceeding* the GKZ bound, if these originate from neutron stars *within* the Milky Way or nearby galaxies.

We thus arrive at an explanation which agrees qualitatively with observations, and at an estimated event rate that is not too far from the one observed. Evidently, there remain many uncertainties in our calculation, quite apart from questions concerning the viability of the unification scenario proposed in [5]. Some of these are due to our ignorance of the detailed dynamics, others are due to untested extrapolations and yet others are due to our insufficient knowledge of astrophysical data and difficult issues with strong interaction dynamics in neutron stars (and their composition, density and age profile, in particular). Nevertheless, we find it remarkable that the present proposal could tie in with the scheme proposed in [5] to explain the fermion content of the SM, with three generations of quarks and leptons.

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[19] These assignments follow from an $\mathrm{SU}(3)\times\mathrm{U}(1)$ decomposition of the $N=8$ supergravity gravitinos, *except* for the shift of the U(1) charges that was originally introduced in [9] to make the electric charge assignments of the spin-$\frac{1}{2}$ fermions agree with those of the quarks and leptons. As shown in [5, 12, 13], it is this latter shift which requires enlarging the SU(8) R symmetry of $N=8$ supergravity to $K(E_{10})$, and which takes the construction 'beyond' $N=8$ supergravity.
[20] In the calculations below we will usually neglect irrelevant factors of $\mathcal{O}(1)$, as with current knowledge we anyhow cannot pretend to a higher level of precision.
[21] We take this opportunity to correct a mistake in [6]: the claim that the gravitinos can never be in thermal equlibrium only applies to non-strongly interacting gravitinos, whereas for the strongly interacting ones the abundance follows from the argument given below.
[22] Whereas for the cross section in (2) the relevant quantity is the relative velocity γ which in our case is very close to one.