Planck Mass Charged Gravitino Dark Matter

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Following up on our earlier work predicting fractionally charged and strongly interacting very massive gravitinos we discuss possible signatures and propose possible ways of their detection.

1. Introduction. In very recent work [1] we have raised the possibility that, very unconventionally, dark matter (DM) could consist at least in part of very massive stable gravitinos which are furthermore fractionally charged and possibly strongly interacting. In this note 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 DM models where the masses of putative DM constituents range from fractions of an eV (for axion-like DM) to the TeV scale (WIMPs or WIMPZILLAs); for supersymmetric DM candidates there is a particularly large variety of DM mass ranges, owing to the large number of different models. With large mass a crucial issue is that of stability because Planck mass 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 survival to the present epoch. Indeed, so far there have been only sporadic attempts at incorporating Planck mass DM constituents [2–4], and they all rely on DM particles that are subject to gravitational interactions only. The crucial new and necessary feature ensuring stability here is the *fractional charge* of the DM candidates.

As explained in [1] our proposal is based on an attempt to embed Standard Model (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 (following a proposal originally due to [5], see also [6]). We stress that 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 combination of eight massive gravitinos and 48 spin-$\frac{1}{2}$ fermions forms an irreducible unfaithful spinorial representation of K(E$_{10}$) [7, 8]. The unaccustomed 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. 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, the main motivation for our proposal comes from the fact that it can make do with just the observed three generations of quarks and leptons (including right chiral neutrinos), in accord with indications from LHC that the SM could survive more or less *as is* up to the Planck scale, and in contrast to numerous currently popular scenarios postulating a plethora of new particles at the TeV scale.

2. Main new features. Our proposal implies a number of highly unusal features for the gravitinos. We caution readers that these features rely on a number of assumptions that are contingent on the proposal of [9] 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 deemerge. With this caveat 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, supersymmetry might actually be never realized at *any* energy as a field theoretic symmetry.

2. The eight massive gravitinos split as $\mathbf{3} \oplus \bar{\mathbf{3}} \oplus \mathbf{1} \oplus \mathbf{1}$ under SU(3). Identifying this SU(3) with SU(3)$_c$ (as we did in [1]), a complex triplet of gravitinos would be subject to strong interactions. All gravitinos carry *fractional electric charges*, to wit, $\frac{1}{3}$ (or $-\frac{1}{3}$) for colored (or anticolored) gravitinos and $\pm\frac{2}{3}$ for color singlets (the alternative option of identifying SU(3) with the family symmetry SU(3)$_f$ is disfavored for the reasons explained in [1]).

3. The color non-singlet gravitinos should form bound states with quarks so as to avoid colored final states for temperatures $T < \Lambda_{QCD}$. Importantly, with the known SU(3)$_c$ assignments of the SM quarks there

is no way to combine them with the color triplet gravitinos to build color singlet states that are *not* fractionally charged. Of course, an important open question here concerns the strong interaction dynamics of superheavy colored particles. We here appeal to heavy quark theory (see e.g. [10]), where the confinement scale is set by the difference between the mass of the bound state meson and the mass of the heavier constituent. This difference is usually of the order of Λ_{QCD}.

4. Despite their strong and electromagnetic interactions with ordinary matter, the Planck mass gravitinos would be stable. This is due to their fractional charge, because there simply are no fractionally charged final states in the SM which they could decay into. Because the main interaction relevant for our discussion here is the electromagnetic one, similar conclusions hold for the two remaining color neutral gravitinos, which combine into one complex (Dirac) gravitino, whence they are likewise stable. Being stable all these color neutral particles should be around us, though in low abundance, see below.

5. Importantly, Planck mass particles are never in thermal equilibrium during the evolution of the Universe after the Planck era, so common astrophysical wisdom (see e.g. [11]) 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 density of particles of mass m and σ the annihilation cross section. For small velocities $\sigma v \sim \alpha(m)^2/m^2$ ($\alpha(m) = g(m)^2/(4\pi)$, where $g(m)$ is the relevant gauge coupling evaluated at energy scale m). Thermal equilibrium requires $\Gamma \gtrsim H \sim T^2/M_{\rm PL}$ [12], so with $n = g(mT/(2\pi))^{3/2}e^{-m/T}$ for massive particles ($g = 4$ for each massive gravitino species) this constraint translates into the condition

$$\left(\frac{m}{T}\right)^{\frac{1}{2}} e^{-m/T} \gtrsim \frac{m}{\alpha(m)^2 M_{\rm PL}} \qquad (1)$$

which for $m \sim M_{\rm PL}$ and $T < M_{\rm PL}$ can never be satisfied (note that $\alpha(m) \lesssim O(0.1)$ for all SM gauge couplings over the whole range of energies from the weak scale up to $M_{\rm PL}$). In other words, the Planck mass DM gravitinos would be frozen out from the very beginning and their abundance thus cannot be estimated from thermal equilibrium but requires a "pre-Planckian" explanation.

6. If any signatures of this type are 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 hole holes our gravitinos are very close to, but strictly below extremality (because $\frac{2}{3} < 1$!).

Let us recall that in conventional scenarios of low energy supersymmetry and supergravity, gravitinos do *not* carry charge (this would require N-extended supergravities with at least $N \geq 2$, but these are usually dismissed because for $N > 1$ one cannot have chiral gauge interactions with non-composite gauge bosons). Depending on their mass the neutral gravitinos of $N = 1$ supergravity can in principle decay into lighter supersymmetric particles (neutralinos) via the Noether interaction present in any supergravity Lagrangian; if they are too light to decay they would themselves contribute to DM. Either of these scenarios is completely different from the present one. By contrast, decays of our gravitino DM candidates are excluded because of the absence of fractional charge in the final SM states, despite their interactions with SM matter. We note that also in superstring models there are in principle "extended" gravitinos, but these are usually not considered, as they do not carry SM charges, and are assumed to decay very quickly, being 'obviously' unstable. So in the present scenario it is precisely the exotic feature of fractional charge that can make Planck mass gravitinos survive to the present epoch.

The possibility of DM carrying SM charges (usually referred to as CHAMPs [13]) has already been considered in the literature, although not very prominently because DM is usually assumed to interact only gravitationally. Such analyses are obviously very model dependent, see e.g. [13], and usually apply only to much lighter DM constituents, so accepted cosmological bounds are invalid for the case of masses of the order of Planck 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 [14]

$$|q| \lesssim 7.6 \cdot 10^{-10} \left(\frac{m}{1\,{\rm TeV}}\right)^{\frac{1}{2}} \qquad (2)$$

with 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 $\lesssim \mathcal{O}(1\,{\rm TeV})$ 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 the DM particle to have Planck scale mass, then the admissible charge comes out to be of order unity: for $m \sim 10^{19}$ GeV the above formula gives

$$|q| \lesssim 7.6 \cdot 10^{-2} \qquad (3)$$

Taking into account the theoretical uncertainties and model dependencies, this value is very well compatible

with charges of order one!

3. Prospects of detection. What are the prospects for actually detecting such DM candidates? Surprisingly, here the large mass value can come to our help: it is a well known result in general relativity that in the course of the expansion of the Universe any peculiar motion of a massive particle out of equilibrium decreases without interactions to zero with the increase of the scale factor. So whatever the initial velocity distribution was shortly after the Planck era, it is reduced by a factor of $a_{\rm PL}/a_{now} \sim 10^{-30}$, 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 w.r.t. the CMB rest frame, with a small velocity dispersion due to their interactions. Fortunately, they nevertheless do move relative to the Earth. First of all, we recall that the Earth moves relative to the CMB rest frame, so any particle at rest w.r.t. the CMB moves with relative velocity w.r.t. to us (~ 370 km/s with small seasonal variations). Moreover, the DM gravitinos will be trapped by the solar or galactic gravitational field and thus end up on some geodesic orbit. Remarkably, the escape velocity from the Milky Way galaxy at distances of order 10 kpc from the center of the galaxy is of the same order of magnitude as the relative velocity of our galaxy w.r.t. the CMB. This is indeed a necessary prerequisite for them to be DM candidates because if the escape velocity were much lower, the particle could not be trapped by the galaxy. In conclusion we would expect our DM candidates to move with an effective velocity of some tens or hundreds of kilometers per second w.r.t. Earth (this follows also from from simple considerations based on the virial theorem in Newtonian physics). In this case their non-relativistic kinetic energy is of order

$$E = \frac{1}{2}mv^2 \sim 10^{22} \text{ eV} \tag{4}$$

To estimate their penetration depth we recall that a proton of velocity 300 km/s (i.e. with kinetic energy ~ 0.5 keV) in iron loses approximately 300 MeV per centimeter [15]. Being subject to similar electromagnetic interactions this implies a similar energy loss rate for our DM candidates, so their their range would be

$$R \sim \frac{E}{300 \text{ MeV/cm}} \sim 3 \cdot 10^{13} \text{ cm} \tag{5}$$

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 along the path, leaving a very long straight track. This track would have a lateral extension of a few nanometers, and would thus not be visible in ordinary light.

To estimate the flux, we recall that the estimated mass density of DM in our galaxy in the proximity of the Solar System is $\sim 10^6$ GeV·m^{-3} [16]. If DM is made out of Planck mass particles, this means roughly 10^{-13} particles per cubic meter, that is, a very low abundance which compensates for the very large DM constituent mass.

Putting in the estimated velocity we arrive at a flux estimate of

$$L \lesssim 10^{-9} \text{m}^{-2}\text{s}^{-1} \tag{6}$$

Due to the large degree of ionization any track produced by a Planck mass ionizing particle should be easily detectable by any standard kind of particle detector. Unfortunately, the above rate is probably too low because the average time between two such events would exceed the lifetime of a standard particle physics experiment. However, at this point we can invoke the fact that, during its lifetime of about 4.5 billion years, the Earth will have 'swept up' many such tracks, in such a way that in favorable circumstances we should get many tracks per cubic centimeter. The idea is therefore to look for long uniformly ionized tracks in very old and ultrastable rock or crystals (diamond?). The reason the material needs to be ultrastable is that in normal matter tracks with nanometer lateral extension can be easily erased by all kinds of disturbances ('healing', diffusion, chemical processes, seismic motion, etc.). Nevertheless, assuming they can be detected, such uniform tracks can be easily discriminated against tracks produced by known charged elementary particles. Namely, the latter are either non-relativistic, in which case they get stopped immediately, or otherwise they are relativistic, in which case most of their energy goes into synchroton radiation and not into ionization, and only very short ionized tracks are produced at the end (such short tracks may also be due to nuclear recoil from neutrinos).

We finally note that searches for ionized tracks coming from DM particles have a long history, but to the best of our knowledge all searches so far have concentrated on mass $\lesssim O(1)$ TeV particles of cosmic or accelerator origin, such as for example MoEDAL [17] at CERN which focuses on tracks emanating from interaction vertices. Tracks originating from charged Planck mass gravitinos might actually have already appeared, but being very different may have been simply missed or discarded. Another option to look for such tracks is 'crystal tomography' based on the EPR (Electron Paramagnetic Resonance) technique. There is also a project to detect tracks in old rocks [18]. At any rate, the task of searching for such tracks (assuming they have not been erased in course of the Earth's history) would pose an extraordinary experimental challenge.

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