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Superweakly Interacting Massive Particles

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We investigate a new class of dark matter: superweakly interacting massive particles (super-WIMPs). As with conventional WIMPs, super-WIMPs appear in well motivated particle theories with naturally the correct relic density. In contrast to WIMPs, however, super-WIMPs are impossible to detect in all conventional dark matter searches. We consider the concrete examples of gravitino and graviton cold dark matter in models with supersymmetry and universal extra dimensions, respectively, and show that super-WIMP dark matter satisfies stringent constraints from big bang nucleosynthesis and the cosmic microwave background.

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There is ample evidence that luminous matter makes up only a small fraction of all matter in the Universe. Results from the Wilkinson Microwave Anisotropy Probe, combined with other data, constrain the nonbaryonic dark matter density to $\Omega_{\rm DM} = 0.23 \pm 0.04$ [1], far in excess of the luminous matter density. We therefore live in interesting times: while the amount of dark matter is becoming precisely known, its identity remains a mystery.

WIMPs, weakly interacting massive particles with weak-scale masses, are particularly attractive dark matter candidates. WIMPs have several virtues. First, their appearance in particle physics theories is independently motivated by the problem of electroweak symmetry breaking. Second, given standard cosmological assumptions, their thermal relic abundance is naturally that required for dark matter. Third, the requirement that WIMPs annihilate efficiently enough to give the desired relic density generically implies that WIMP-matter interactions are strong enough for dark matter to be discovered in current or near future experiments.

Here we consider a new class of nonbaryonic cold dark matter: superweakly interacting massive particles (super-WIMPs or SWIMPs). As with WIMPs, super-WIMPs appear in well-motivated theoretical frameworks, such as supersymmetry and extra dimensions, and their (nonthermal) relic density is also naturally in the desired range. In contrast to conventional WIMPs, however, they interact superweakly and so evade all direct and indirect dark matter detection experiments proposed to date.

For concreteness, we consider two specific super-WIMPs: gravitinos in supersymmetric theories and Kaluza-Klein (KK) gravitons in theories with extra dimensions. Gravitino and graviton super-WIMPs share many features, and we investigate them in parallel.

For gravitino super-WIMPs, we consider supergravity, where the gravitino $\tilde{G}$ and all standard model (SM) superpartners have weak-scale masses. Assuming R-parity conservation, the lightest supersymmetric particle (LSP) is stable. In supergravity, the LSP is usually assumed to be a SM superpartner. Neutralino LSPs are excellent WIMP candidates, giving the desired thermal relic density for masses of 50 GeV to 2 TeV, depending on Higgsino content. In contrast, here we assume a $\tilde{G}$ LSP. The gravitinos considered here couple gravitationally and form cold dark matter, in contrast to the case in low-scale supersymmetry breaking models where light gravitinos couple more strongly and form warm dark matter.

We consider also the possibility of graviton dark matter in universal extra dimensions (UED), in which gravity and all SM fields propagate [2]. We focus on $D = 5$ spacetime dimensions with coordinates $x^M = (x^\mu, y)$. The fifth dimension is compactified on the orbifold S^1/Z_2, where S^1 is a circle of radius R and Z_2 corresponds to $y \to -y$. Unwanted massless fields are removed by requiring suitable transformations under $y \to -y$. For example, the 5D gauge field $V_M(x, y)$ transforms as $V_\mu(x, y) \to V_\mu(x, y)$ and $V_5(x, y) \to -V_5(x, y)$ under $y \to -y$, which preserves $V_\mu^0(x)$ and removes $V_5^0(x)$. Similar choices remove half of the fermionic degrees of freedom, producing chiral 4D fermions, and preserve the 4D graviton $h^0_{\mu\nu}(x)$ while removing $h^0_{\mu 5}(x)$ and $h^0_{5\nu}(x)$. The graviscalar $h^0_{55}(x)$ remains; we assume that some other physics stabilizes this mode and generates a mass for it.

The orbifold compactification breaks KK number conservation, but preserves KK parity. KK particles must therefore be produced in pairs, and current bounds require only $R^{-1} \gtrsim 200$ GeV [2,3]. KK parity conservation also makes the lightest KK particle (LKP) stable and a dark matter candidate. For $R^{-1} \sim$ TeV, weakly interacting KK particles have thermal relic densities consistent with observations [4]. In particular, B^1, the first KK partner of the U(1) gauge boson, has been shown to be a viable WIMP dark matter candidate, with promising prospects for direct detection [5,6] and also indirect detection in antimatter searches [5], neutrino telescopes [5,7,8], and gamma ray detectors [5,8].

As in the case of supersymmetry, however, the lightest partner need not be a SM partner. In UED, the LKP could be G^1, the first KK partner of the graviton. G^1 is, in fact, perhaps the most natural LKP candidate—radiative contributions to KK masses, typically positive [9], are negligible for G^1. G^1 couplings are also gravitational and so highly suppressed.

Gravitinos and gravitons therefore naturally emerge as super-WIMP candidates: stable massive particles with superweak interactions. Their weak gravitational interactions imply that they play no role in the thermal history of the early Universe. (We assume inflation followed by reheating to a temperature low enough to avoid regenerating large numbers of super-WIMPs.) Thus, if the next lightest supersymmetric particle (NLSP) or next lightest KK particle (NLKP) is weakly interacting, it freezes out with a relic density of the desired magnitude. Much later, however, these WIMPs then decay to super-WIMPs; as the WIMP and super-WIMP masses are similar, the super-WIMP then inherits the desired relic density.

Unlike WIMPs, however, super-WIMPs are impossible to discover directly, and their annihilation rate is so suppressed that they also escape all indirect detection experiments. At the same time, unlike superheavy dark matter candidates with only gravitational interactions [10], super-WIMPs inherit the desired relic density from a thermal abundance and arise from accessible electroweak physics. At colliders, WIMP decays to super-WIMPs will occur long after the WIMP leaves the detector. If the NLSP or NLKP is neutral, its metastability will have no observable consequences. The discovery of a seemingly stable but charged NLSP or NLKP may, however, provide a strong hint for super-WIMP dark matter.

We now investigate constraints on and alternative signals of super-WIMP dark matter scenarios. The observable consequences of super-WIMPs must rely on the decays of WIMPs to super-WIMPs on cosmological time scales [11]. The NLSP or NLKP may be any SM partner. In supergravity, the lightest SM superpartner is often the Bino $\tilde{B}$, the superpartner of the hypercharge gauge boson. In the minimal UED scenario [2,9], the lightest SM KK mode is often B^1. Motivated by these results, we now consider specific scenarios in which decays to super-WIMPs are typically accompanied by photons, and we consider the impact of electromagnetic cascades.

In the supersymmetric photon super-WIMP scenario, NLSP decay is governed by the coupling $-\frac{i}{8M_*}\bar{\tilde{G}}_\mu[\gamma^\nu,\gamma^\rho]\gamma^\mu\tilde{B}\,F_{\nu\rho}$, where F is the U(1) field strength, and $M_* = (8\pi G_N)^{-1/2} \simeq 2.4\times 10^{18}$ GeV is the reduced Planck scale. The NLSP decay width is

$$\Gamma(\tilde{B}\to\tilde{G}\gamma) = \frac{\cos^2\theta_W}{48\pi M_*^2}\frac{m_{\tilde{B}}^5}{m_{\tilde{G}}^2}\left[1-\frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2}\right]^3\left[1+3\frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2}\right]. \quad (1)$$

In models with low-scale supersymmetry breaking, $m_{\tilde{G}} \ll m_{\tilde{B}}$, and the gravitino couples dominantly through its $\pm\frac{1}{2}$ spin components. In the high-scale supersymmetry breaking scenarios considered here, however, the couplings of the $\pm\frac{3}{2}$ spin polarizations are of the same order and must be kept in deriving Eq. (1).

The properties of gravitons in UED scenarios may be determined straightforwardly; details will be presented elsewhere [12]. Graviton super-WIMPs couple to B^1 through $\frac{\sqrt{2}}{M_*}G^1_{\mu\nu}(-F^{0\mu\rho}F^{1\nu}_\rho + \frac{1}{4}\eta^{\mu\nu}F^0_{\rho\sigma}F^{1\rho\sigma})$, where $F^n_{\mu\nu} \equiv \partial_\mu B^n_\nu - \partial_\nu B^n_\mu$. The $G^1B^1B^0$ vertex is identical to the $G^0B^0B^0$ vertex, and the longitudinal component of the massive B^1 plays no role. The NLKP decay width is

$$\Gamma(B^1\to G^1\gamma) = \frac{\cos^2\theta_W}{72\pi M_*^2}\frac{m_{B^1}^7}{m_{G^1}^4}\left[1-\frac{m_{G^1}^2}{m_{B^1}^2}\right]^3 \times\left[1+3\frac{m_{G^1}^2}{m_{B^1}^2}+6\frac{m_{G^1}^4}{m_{B^1}^4}\right]. \quad (2)$$

The $\tilde{B}$ and B^1 lifetimes are given in Fig. 1. In both cases, in the limit $\Delta m \equiv m_{\rm WIMP} - m_{\rm SWIMP} \ll m_{\rm SWIMP}$, the WIMP lifetime is proportional to $(\Delta m)^{-3}$ and is independent of the overall mass scale.

As we will see, the most relevant bounds constrain the total energy released in photons in WIMP decay, or more precisely, $\varepsilon_\gamma Y_\gamma$, where ε_γ is the energy of the photons when created and $Y_\gamma = n_\gamma/n_\gamma^{\rm BG}$ is the number density of photons from WIMP decay normalized to the number density of background photons $n_\gamma^{\rm BG} = 2\zeta(3)T^3/\pi^2$, where T is the temperature during WIMP decay. In the super-WIMP scenario, WIMPs decay essentially at rest, and so $\varepsilon_\gamma = (m^2_{\rm WIMP} - m^2_{\rm SWIMP})/(2m_{\rm WIMP})$. Since a super-WIMP is produced in association with each photon, $Y_\gamma = Y_{\rm SWIMP}$, and the photon abundance is given by

$$Y_{\rm SWIMP} \simeq 3.0\times 10^{-12}\left[\frac{\rm TeV}{m_{\rm SWIMP}}\right]\left[\frac{\Omega_{\rm SWIMP}}{0.23}\right]. \quad (3)$$

Predicted values for $\varepsilon_\gamma Y_{\rm SWIMP}$ are shown in Fig. 2.

As evident in Fig. 1, WIMP decays occur long after big bang nucleosynthesis (BBN) and so may, in principle, destroy the successful BBN predictions for light element

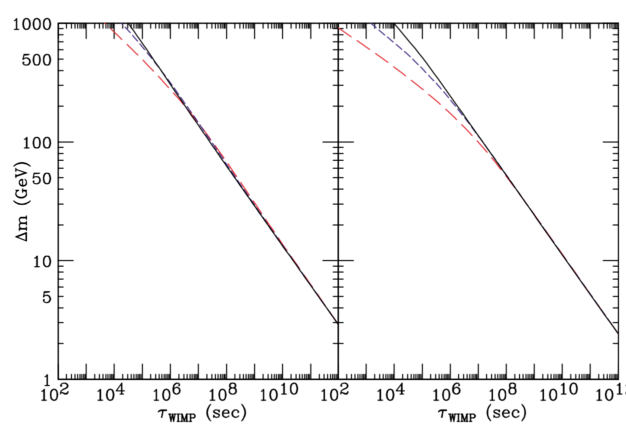

FIG. 1 (color online). Lifetimes for $\tilde{B}\to\tilde{G}\gamma$ (left) and $B^1\to G^1\gamma$ (right) for $\Delta m \equiv m_{\rm WIMP} - m_{\rm SWIMP}$ and $m_{\rm SWIMP} =$ 0.1 TeV (long-dashed line), 0.3 TeV (short-dashed line), and 1 TeV (solid line).

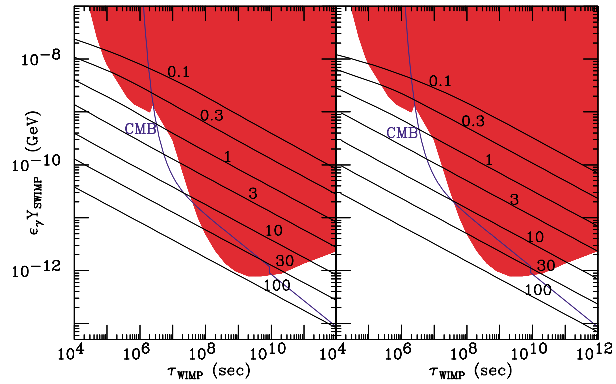

FIG. 2 (color online). The photon energy release $\varepsilon_\gamma Y_{\mathrm{SWIMP}}$ for various m_{SWIMP} in TeV in the gravitino (left) and graviton (right) super-WIMP scenarios. We fix $\Omega_{\mathrm{SWIMP}} = 0.23$; $\varepsilon_\gamma Y_{\mathrm{SWIMP}}$ scales linearly with Ω_{SWIMP}. BBN constraints exclude the shaded regions [13]; consistency of the CMB with a black-body spectrum excludes regions above the CMB contours.

abundances. The energy of photons produced in late decays is rapidly redistributed through scattering off background photons, $\gamma\gamma_{\mathrm{BG}} \to e^+e^-$, and inverse Compton scattering [14,13]. As a result, the constraints of BBN are, to an excellent approximation, independent of the initial energy distribution of injected photons and constrain only the total energy release.

Detailed analysis [13], demanding consistent predictions for deuterium, ^{3}He, ^{4}He, ^{6}Li, and ^{7}Li, excludes the region of parameter space shown in Fig. 2. The BBN constraint is weak for early decays: at early times, the Universe is hot and the initial photon spectrum is rapidly softened, leaving few high energy photons above threshold to modify the light element abundances. We find that BBN excludes some of the relevant parameter region, but not all. In particular, for relatively short-lived WIMPs with $\tau \lesssim 10^7$ s and weak-scale masses, the requirement that super-WIMPs form all of the dark matter is consistent with the constraints from BBN.

The cosmic microwave background (CMB) also imposes constraints [15,16]. The injection of energy in the form of photons may distort the CMB from the observed black-body spectrum. Before redshifts of $z \sim 10^7$, elastic Compton scattering, bremsstrahlung $eX \to eX\gamma$ (with X an ion), and double Compton scattering $e^-\gamma \to e^-\gamma\gamma$ effectively thermalize injected energy. After $z \sim 10^7$, however, the photon number-changing interactions become ineffective, and the photon spectrum relaxes only to a Bose-Einstein distribution with chemical potential μ. After $z \sim 10^5$, even Compton scattering becomes ineffective, and deviations from the black-body spectrum may be parametrized by the Sunyaev-Zeldovich y parameter.

As with the BBN constraints, bounds from the CMB are largely independent of the injected energy spectrum, depending primarily on the total energy release. The bounds on $\varepsilon_\gamma Y_{\mathrm{SWIMP}}$ scale linearly with the bounds on μ and y. We update the analysis of Ref. [15] to include the latest results $|\mu| < 9 \times 10^{-5}$ and $|y| < 1.2 \times 10^{-5}$ [17], with baryon density $\Omega_B h^2 \simeq 0.022$ [1], where $h \simeq 0.71$ is the normalized Hubble expansion rate. These bounds exclude energy releases above the CMB contours in Fig. 2. Remarkably, the CMB constraints are now so precise that they supersede BBN constraints for decay times $\tau \sim 10^7$ s and $\tau \gtrsim 10^{10}$ s. Nevertheless, regions of super-WIMP parameter space, including regions with weak-scale masses and mass splittings, remain viable.

Finally, for highly degenerate WIMP-SWIMP pairs, WIMPs decay very late to soft photons. The photon spectrum is not thermalized and may produce observable peaks in the diffuse photon spectrum. The present differential flux of photons from WIMP decay is

$$\frac{d\Phi}{dE_\gamma} = \frac{c}{4\pi}\int_0^{t_0} \frac{dt}{\tau_{\mathrm{WIMP}}} \frac{N_{\mathrm{WIMP}}(t)}{V_0} \delta\left(E_\gamma - \frac{\varepsilon_\gamma}{1+z}\right), \quad (4)$$

where $t_0 \simeq 13.7$ Gyr is the age of the Universe [1], $N_{\mathrm{WIMP}}(t) = N_{\mathrm{WIMP}}^{\mathrm{in}} e^{-t/\tau_{\mathrm{WIMP}}}$, where $N_{\mathrm{WIMP}}^{\mathrm{in}}$ is the number of WIMPs at freezeout, and V_0 is the present volume of the Universe. The diffuse photon flux is a sensitive probe only when WIMPs decay in the matter-dominated era. We may then take $1 + z = (t_0/t)^{2/3}$, and

$$\frac{d\Phi}{dE_\gamma} \simeq \frac{3c}{8\pi} \frac{N_{\mathrm{WIMP}}^{\mathrm{in}}}{V_0 \varepsilon_\gamma}\left[\frac{t_0}{\tau_{\mathrm{WIMP}}}\right]^{2/3} F(a)\Theta(\varepsilon_\gamma - E_\gamma), \quad (5)$$

where $F(a) = a^{1/2}e^{-a^{3/2}}$, $a = (E_\gamma/\varepsilon_\gamma)(t_0/\tau_{\mathrm{WIMP}})^{2/3}$. $F(a)$ is maximal at $a = 3^{-2/3}$, and so, for $\tau_{\mathrm{WIMP}} < t_0$, the differential photon flux reaches its maximal value at

$$E_\gamma^{\max} = \varepsilon_\gamma\left[\frac{\tau_{\mathrm{WIMP}}}{3t_0}\right]^{2/3} = 680\ \mathrm{keV}\left[\frac{\mathrm{GeV}}{\Delta m}\right] \quad (6)$$

for gravitinos, and an energy 1.4 times smaller for gravitons. The Δm dependence follows from the redshifting of photons created with energy Δm by $1 + z \propto \tau_{\mathrm{WIMP}}^{-2/3} \propto (\Delta m)^2$. For high degeneracies,

$$\frac{N_{\mathrm{WIMP}}^{\mathrm{in}}}{V_0} = 1.2 \times 10^{-9}\ \mathrm{cm}^{-3}\left[\frac{\mathrm{TeV}}{m_{\mathrm{SWIMP}}}\right]\left[\frac{\Omega_{\mathrm{SWIMP}}}{0.23}\right], \quad (7)$$

and so the maximal flux is

$$\frac{d\Phi}{dE_\gamma}(E_\gamma^{\max}) = 1.5\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{MeV}^{-1} \times \left[\frac{\mathrm{TeV}}{m_{\mathrm{SWIMP}}}\right]\left[\frac{\Delta m}{\mathrm{GeV}}\right]\left[\frac{\Omega_{\mathrm{SWIMP}}}{0.23}\right] \quad (8)$$

for gravitinos, and a factor of 1.4 larger for gravitons.

Representative photon energy spectra are shown in Fig. 3. Also shown are the measured diffuse fluxes from the observatories HEAO, OSSE, and COMPTEL [18], determined from observed fluxes by subtracting known point sources. The observed spectra fall rapidly with energy and so severely constrain the relatively hard photon spectra predicted by $\Delta m \lesssim 10$ GeV. Note that we have not included photon interactions which soften the

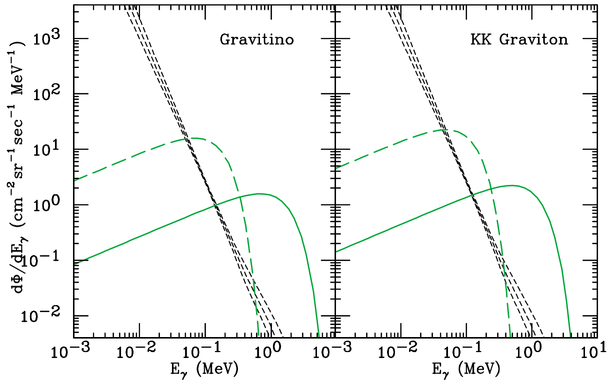

FIG. 3 (color online). Diffuse photon fluxes (solid line) for $m_{\mathrm{SWIMP}} = 1$ TeV, $\Omega_{\mathrm{SWIMP}} = 0.23$, and $\Delta m = 1$ GeV (solid line) and 10 GeV (long-dashed line), and upper bounds from observations (short-dashed line).

photon spectrum for $\Delta m \gtrsim$ few GeV [19]; such effects can only enlarge the allowed parameter space discussed below.

In Fig. 4, we compile the constraints discussed above and show the allowed regions of the $(m_{\mathrm{SWIMP}}, \Delta m)$ plane for the photon gravitino and graviton super-WIMP dark matter scenarios. The BBN and CMB constraints are as discussed above. An additional region is excluded by the requirement that the diffuse photon flux never exceed the observed flux by 2σ for any energy. Although these data exclude some of the parameter space, the most well-motivated region with $m_{\mathrm{SWIMP}}, \Delta m \sim 100$ GeV to 1 TeV, remains an outstanding possibility.

In conclusion, we find that super-WIMPs provide a qualitatively novel possibility for particle dark matter. Such particles appear in the form of gravitinos and gravitons in theories with supersymmetry and extra dimensions, and they naturally inherit the desired relic density from late-decaying weakly interacting NLSPs or NLKPs.

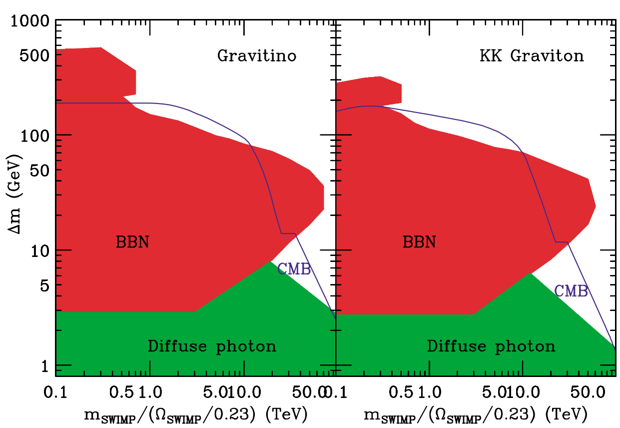

FIG. 4 (color online). Regions of the $(m_{\mathrm{SWIMP}}, \Delta m)$ plane excluded by BBN, CMB, and diffuse photon constraints. The shaded regions and the regions below the CMB contours are excluded.

SuperWIMPs satisfy existing constraints from BBN and CMB and evade all conventional dark matter experiments. On the surface, we have apparently committed Pauli's "ultimate sin" by proposing a solution to the dark matter problem that has no observable consequences. However, improvements in the measurements discussed above may uncover anomalies. For example, a detailed study of the 15 keV to 10 MeV diffuse photon flux by the International Gamma-Ray Astrophysics Laboratory is currently underway [20]. A pronounced bump in this spectrum could provide a striking signal of super-WIMP dark matter. Finally, we note that neutrino, charged lepton, weak gauge boson, and Higgs boson NLSPs and NLKPs are all viable from the point of view of preserving the naturalness of the desired relic density. Some of these scenarios may be severely constrained by bounds on hadronic showers, but the remaining scenarios will have qualitatively different, and possibly very interesting, observational consequences.

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