Direct Detection Constraints on Superheavy Dark Matter

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The dark matter in the Universe might be composed of superheavy particles (mass $\gtrsim 10^{10}$ GeV). These particles can be detected via nuclear recoils produced in elastic scatterings from nuclei. We estimate the observable rate of strongly interacting supermassive particles (simpzillas) in direct dark matter search experiments. The simpzilla energy loss in Earth and in the experimental shields is taken into account. The most natural scenarios for simpzillas are ruled out based on recent EDELWEISS and CDMS results. The dark matter can be composed of superheavy particles only if these interact weakly with normal matter or if their mass is above 10^{15} GeV.

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The dark matter in the Universe might be composed of supermassive particles (mass $\gtrsim 10^{10}$ GeV). Although the leading dark matter candidate is a weakly interacting massive particle (WIMP), recent models for nonthermal production of particles in the early Universe have broadened the dark matter mass and cross section parameter space. Supermassive particles avoid the unitarity mass bound [1] by not being thermal relics of the big bang. There are many ways to produce supermassive particles in the early Universe. The most general way is gravitational production at the end of inflation as a result of the expansion of the Universe [2–4]. In this scenario, the average particle density is independent of the interaction strength with normal matter.

A reasonable assumption for the mass of such particles is the inflaton mass scale, $\sim 10^{12}$ GeV in chaotic inflation models. These particles might be composed of exotic quarks or other new particles [5,6]. Their production allows them to be electrically charged but there are arguments that they have to be neutral [5].

If the nonluminous matter is indeed composed of supermassive particles, its interaction strength with normal matter can range from weak (wimpzillas [7]) to strong (simpzillas [8]). Although not many experiments have been built to search for strongly interacting dark matter, observations from several experiments constrain their mass and cross section parameter space [9,10]. Masses up to about 10^4 GeV are ruled out and several allowed regions were found above this mass for a cross section range of about 10^{-32} to 10^{-15} cm^2. Stronger constraints can be found in [11].

Here we consider the direct detection of simpzillas. Direct detection experiments measure the energy deposited by a nuclear recoil produced in the particle scattering from a nucleus. Their main goal is to detect WIMPs. We show that direct detection experiments are also able to probe simpzillas as a dark matter candidate. Comparison of our estimated simpzilla detection rate with the latest CDMS [12] and EDELWEISS [13,14] results rules out the most natural scenarios of the simpzilla parameter space.

A simpzilla arriving at an underground detector will have interacted many times in Earth and, depending on its interaction cross section with ordinary matter, will interact many times in the detector itself. To determine if simpzillas can be directly detected, their energy degradation and range in Earth and the experimental shield has to be taken into account.

We assume that the local dark matter is composed entirely of simpzillas, with a density of 0.3 GeV/cm^3. The total energy deposited (Q) in a detector is given by the nuclear recoil energy (E_R) times the number of simpzilla interactions in the detector $N_I \sim n_N \sigma_{\chi N} l$, where n_N is the detector atomic number density, $\sigma_{\chi N}$ is the simpzilla-nucleus cross section, and l is the detector thickness. We assume that the simpzilla-nucleus cross section is independent of the nuclear spin and relates to the simpzilla-nucleon cross section ($\sigma_{\chi p}$) by $\sigma_{\chi N} = \sigma_{\chi p}\,(A\, m_r/m_{rp})^2$, where A is the nucleus atomic number, m_r is the nucleus-simpzilla reduced mass given by $m_\chi m_N/(m_\chi + m_N)$, m_χ is the simpzilla mass, m_N is the nucleus mass, and m_{rp} is the nucleon-simpzilla reduced mass. As $m_\chi \gg m_N$, the reduced masses are simply the nucleus and the nucleon mass, respectively.

The nuclear recoil energy is given by

$$E_R = \frac{|\vec{q}^2|}{2m_N} = m_N v^2 (1 - \cos\theta), \tag{1}$$

where q is the momentum transferred, v is the dark matter velocity, and θ is the scattering angle in the center-of-momentum frame. For a given material and scattering angle, the recoil energy depends only on the simpzilla velocity.

A simpzilla with a cross section of 10^{-26} cm^2 will interact about 10^4 times in a 1 cm thick Ge detector, while it will interact only once if the cross section is 10^{-30} cm^2.

The total mean energy depositions will be about 450 MeV and 45 keV, respectively.

We assume that the dark matter has a Maxwellian velocity distribution $[f(v)]$ with an average velocity v_0 of 220 km/s and includes the motion of Earth ($v_\oplus$) as described in [15,16]:

$$f(v)dv = \frac{v dv}{v_\oplus v_0 \sqrt{\pi}} \left\{ \exp\left[-\frac{(v - v_\oplus)^2}{v_0^2} \right] - \exp\left[-\frac{(v + v_\oplus)^2}{v_0^2} \right] \right\}. \quad (2)$$

The distance (l) traveled through Earth to the detector is a function of the arrival angle between the simpzilla arrival direction at Earth and the normal direction from the detector to Earth's surface. We assume simpzillas are isotropically distributed in the galactic halo. The average simpzilla energy at the detector is given by

$$E = E_0 \exp\left(-\frac{2\rho N_A \sigma_{\chi N}}{m_\chi} l \right), \quad (3)$$

where E_0 is the simpzilla energy at Earth, ρ is the Earth density, and N_A is Avogadro's constant. We use the Earth density profile given by the preliminary earth model [17,18] and its composition found in [19].

Knowing the energy loss in Earth, we determine the maximum distance a simpzilla can travel before being stopped. This distance is related to the maximum arrival angle and defines an acceptance cone. Any simpzilla which reaches Earth at an arrival angle larger than the cone angle will have lost all its energy before reaching the detector. This cone depends on the m_χ and on $\sigma_{\chi p}$. The fraction of Earth contained in the acceptance cone ($f_\oplus$) will therefore define the fraction of incident dark matter particles that reach the detector.

Within an acceptance cone, the average simpzilla velocity (v_{0d}) and energy (E_{0d}) at the detector are determined. The fraction of these events (f_D) with energy below a certain threshold is given by the ratio of the lower velocity events over the total number of events:

$$f_D = \frac{\int_0^{\sqrt{2E_{\max}/m_\chi}} f(v)\, dv}{\int_0^{\sqrt{2E_{\rm esc}/m_\chi}} f(v)\, dv}, \quad (4)$$

where $E_{\max}$ is the maximum energy which can be detected in a given detector and $E_{\rm esc}$ is the maximum simpzilla velocity which we assume to be 650 km/s, the galactic halo escape velocity.

The deposited energy spectrum dR/dQ in the detector is given by

$$\frac{dR}{dQ} = k\left[\frac{dR_1}{dQ} - \frac{R_0}{4E_{0d} m_N} \exp\left(-\frac{v_{esc}^2}{v_{0d}^2} \right) \right], \quad (5)$$

where k is a parameter in the velocity distribution [16]

$$k = \left[\mathrm{erf}\left(\frac{v_{\rm esc}}{v_{0d}} \right) - \frac{2v_{\rm esc}}{\sqrt{\pi} v_{0d}} \exp(-v_{\rm esc}^2/v_{0d}^2) \right]^{-1}, \quad (6)$$

dR_1/dQ is the differential rate including Earth's motion [16],

$$\frac{dR_1}{dQ} = \frac{R_0}{16E_{0d} m_N} \frac{\sqrt{\pi} v_{0d}}{v_\oplus} \left[\mathrm{erf}\left(\frac{v_t + v_\oplus}{v_{0d}} \right) - \mathrm{erf}\left(\frac{v_t - v_\oplus}{v_{0d}} \right) \right], \quad (7)$$

where $v_t = \sqrt{2E_t/m_\chi}$, and

$$R_0 = f_\oplus f_D F^2(Q) \frac{2N_A \rho_0}{\sqrt{\pi} A m_\chi} \sigma_{\chi N} v_{0d}. \quad (8)$$

R_0 includes the fraction of the dark matter which is detectable. Besides containing the terms $f_\oplus$ and f_D which are related to strongly interacting particles, and taking the energy loss into account (which makes $v_{0d} < v_0$), the differential energy spectrum given by Eq. (5) is the same as for WIMPs [16]. For a simpzilla-nucleus interaction, the wavelength $\lambda = \hbar/q$ is smaller than the nuclear radius. The drop in the effective cross section with increasing q is described by a form factor, $F^2(Q)$. We assume that $F^2(Q)$ is well approximated [15,16] by the Woods-Saxon form factor [20].

We consider the CDMS and the EDELWEISS experiments, which employ Ge and, in the case of CDMS, Si detectors operated at mK temperatures [12,13,21]. Currently, CDMS is located at a shallow depth of about 16 mwe at the Stanford Underground Facility (SUF); its final destination is the Soudan mine in Minnesota, at a depth of about 2080 mwe. EDELWEISS is located in the Laboratoire Souterrain de Modane at 4500 mwe.

A particle interacting in a cryogenic Ge or Si detector will create phonons and electron-hole pairs. While phonons are a measure of the total recoil energy, only a fraction of this energy is dissipated into ionization. The simultaneous measurement of the phonon and ionization signals results in an excellent discrimination efficiency against electron recoils, which are caused by the dominant radioactive background. This discrimination is possible because the ratio of ionization to recoil energy is lower for nuclear recoils than for electron recoils.

We estimate the simpzilla elastic scattering rates at both shallow and deep sites. We take into account the simpzilla energy loss in the experimental shields, made of Cu and Pb. For CDMS, we also estimate the energy deposition in the active muon shield, made of plastic scintillator. To determine the simpzilla detection rate, we integrate the differential energy spectrum given by Eq. (5).

Figure 1 shows the detectable simpzilla rate versus simpzilla mass for various cross sections, for CDMS at SUF. Two effects are responsible for the kinks in these curves. First, the fact the experiment is at a shallow depth makes the distance the simpzilla travels in Earth very small for arrival angles smaller than 90° and much larger above 90°. Second, the simpzilla energy loss rate

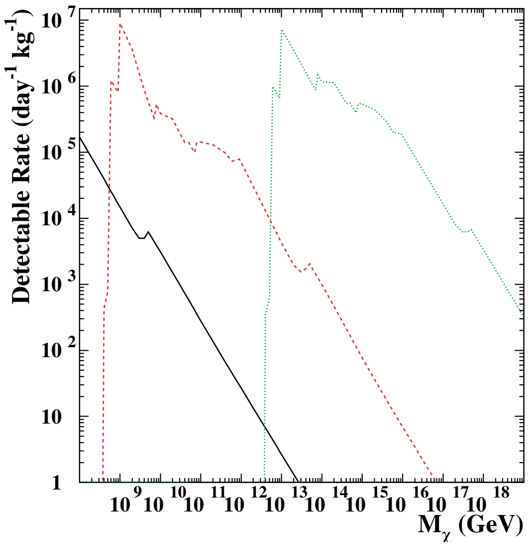

FIG. 1 (color online). Estimated simpzilla rate versus mass for simpzilla nucleon cross sections of 10^{-30}, 10^{-26}, and 10^{-22} cm^2 (from left to right) in the CDMS experiment at the Stanford Underground Facility. Kinks of each curve are due to the shallow depth and to the Earth density profile.

increases with depth, due to the increase in the Earth density.

The simpzilla rate at shallow sites is slightly higher than at deeper sites. As an example, the rates of 10^{12} GeV simpzillas arriving at a CDMS detector at SUF for $\sigma_{\chi p}$ of 10^{-30} and 10^{-26} cm^2 are 27/day/kg and 21×10^4/day/kg, respectively, while 4/day/kg and 17×10^4/day/kg, respectively, at the EDELWEISS site.

To obtain limits on simpzilla masses and cross sections, we compare the predicted simpzilla detection rates with the background rates of the CDMS and EDELWEISS experiments in different energy regions. We emphasize here that our results will be conservative, for we are not attempting a simpzilla-specific analysis of the data.

We estimate the simpzilla rate in the 10–100 keV recoil energy region for CDMS, and in the 30–100 keV region for EDELWEISS. $E_{\rm max}$ in Eq. (4) is set to 100 keV. We require a minimum nuclear recoil of 1 keV per interaction, since the ionization efficiency in Ge decreases rapidly [22] below this energy. This recoil energy range probes the region where $\sigma_{\chi p}$ is lower than about 10^{-28} cm^2. The $\sigma_{\chi p} = 10^{-30}$ cm^2 curve in Fig. 1 is representative of the predicted rate in this recoil energy region. For CDMS, we also estimate the energy deposited in the 4.1 cm thick plastic scintillator surrounding the detectors. Simpzillas with a cross section below 10^{-24} cm^2 will deposit less than 2 MeV in this active muon shield and thus belong to the category of muon-anticoincident events.

CDMS observed a total of 27 nuclear recoil events (single and multiple scatters) in the 10–100 keV region for an exposure of 15.8 kg-day [12]. This yields a background of 1.7 events/kg/day. Comparing the above number with the number of expected simpzillas in this energy region excludes the region labeled "CDMS" in Fig. 2 at 90% C.L., for cross sections below 10^{-28} cm^2.

EDELWEISS has reported their result [13] for WIMP searches based on an exposure of 11.7 kg day. It is a combined result from two measurements. The first [23], using a 320 g Ge detector, had an effective exposure of 4.53 kg day. No nuclear recoils were found in the 30–200 keV energy range. The second measurement, with a new 320 g Ge detector [13], had an effective exposure of 7.4 kg day and observed no nuclear recoil events from 20–100 keV. Their expected background from neutron scatters is about 0.03 events/kg/day above 30 keV [23]. The combined result corresponds to a rate inferior to 0.2 kg^{-1} day^{-1} at 90% confidence level. Comparing our estimated rate for the EDELWEISS detector with the 0.2 events/kg/day 90% C.L. limit for the 30–100 keV recoil energy region, we exclude the region labeled "EDEL" in Fig. 2, again for $\sigma_{\chi p}$ below 10^{-28} cm^2.

For CDMS, we estimate the simpzilla rates in the 3–10 MeV ionization energy region, and compare it to the background in the same region shown in Fig. 33 in [12]. The muon-anticoincident background in this region is very low, due to the fact that the background from natural radioactivity ends around 2615 keV. We approximate the ionization energy to one-third of the recoil energy. The 1 keV minimum nuclear recoil energy

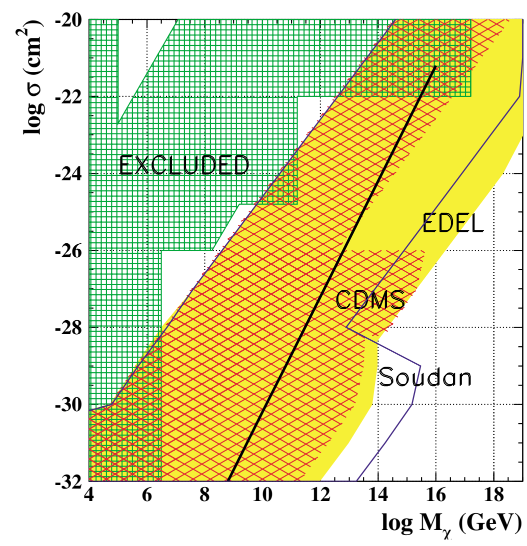

FIG. 2 (color online). Excluded regions at 90% C.L. in the simpzilla mass versus cross section parameter space. The region labeled "excluded" was excluded in the analysis given in [10]; the regions labeled "EDEL" (filled) and "CDMS" (hatched) are excluded based on EDELWEISS [13,23] and CDMS results [12]. The area labeled "Soudan" (within solid line) is the predicted region to be probed by CDMS at Soudan. As a comparison, the region above the thick straight line shows the sensitivity of future, cubic-kilometer sized neutrino telescopes [24].

requirement allows to probe $\sigma_{\chi p}$ of 10^{-26} cm^2 and lower. This comparison excludes, at 90% C.L., the $\sigma_{\chi p}$ region from about 10^{-29} to 10^{-26} cm^2 labeled CDMS in Fig. 2.

Simpzilla with cross sections greater than 10^{-26} cm^2 will interact more that 10^4 times in a 1 cm thick Ge detector, and thus deposit an energy above 10 MeV for a 1 keV threshold per interaction. In spite of their high energy, such events would nonetheless trigger the CDMS and EDELWEISS detectors, giving rise to saturated pulses. To obtain a conservative exclusion region for these cross sections, we consider the total background trigger rate of 0.4 Hz [12] for CDMS and the trigger rate of 20 events/kg/day above an energy of 1.5 MeV [14] for EDELWEISS. Since CDMS triggers on the phonon signal [12], we can relax the threshold per interaction to 1 eV. We assume a low-energy threshold of 5 keV. This excludes the region above 10^{-26} cm^2 in Fig. 2.

Figure 2 also shows the predicted region to be probed by CDMS at the Soudan site. We assume a total exposure of 230 kg day and a muon-anticoincident nuclear recoil background of 0.02 events/kg/day in the 10–100 keV energy region. We also assume an overall trigger rate which is 100 times lower than the one at SUF.

We have investigated the direct detection of strongly interacting supermassive particles. We have estimated the differential and total direct detection rates for the CDMS and EDELWEISS experiments. We find that, although the energy loss as well as the depletion in the number of simpzillas reaching an underground detector are substantial, the predicted nuclear recoil rates are much higher than for supersymmetric WIMPs.

Comparison of our predicted rates for CDMS at SUF and for EDELWEISS with their most recent results [12–14] rules out the most natural simpzilla scenarios. The most natural scenarios are the ones for which the simpzilla mass is comparable to the inflaton mass in chaotic inflation models ($\sim 10^{12}$ GeV) and the simpzilla-nucleon cross section is comparable to the nucleon-nucleon strong interaction cross section. The simpzilla mass versus cross section parameter space which is probed by these two experiments is shown in Fig. 2.

The region to be tested by cubic kilometer neutrino telescopes such as IceCube [24] is also shown. These telescopes can search for secondary neutrinos produced in simpzilla annihilation in the Sun [8,25]. Although most of this region is excluded by direct detection experiments, neutrino telescopes would provide an independent confirmation.

In conclusion, the dark matter in the universe may be composed of superheavy particles only if these particles interact weakly with normal matter or if their mass is above 10^{15} GeV or higher, depending on the simpzilla-nucleon interaction cross section.

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