Superheavy dark matter and ultrahigh energy cosmic rays

R. Dick, K.M. Hopp, and K.E. Wunderle

Abstract: The phase of inflationary expansion in the early universe produces superheavy relics in a mass window between $10^{12} \text{ GeV}$ and $10^{14} \text{ GeV}$. Decay or annihilation of these superheavy relics can explain the observed ultrahigh energy cosmic rays beyond the Greisen-Zatsepin-Kuzmin cutoff. We emphasize that the pattern of cosmic ray arrival directions seen by the Pierre Auger observatory will decide between the different proposals for the origin of ultrahigh energy cosmic rays.

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Résumé: French version of abstract (supplied by CJP if necessary)

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1. Introduction

The nature and origin of the dark matter in the universe and the origin of ultrahigh energy cosmic rays (UHECR) are certainly two of the most interesting problems of astroparticle physics, and maybe even of physics, at the beginning of the 21st century.

The three puzzles related to the origin of cosmic rays with energies beyond the Greisen-Zatsepin-Kuzmin cutoff, $E > E_{\text{GZK}} = 4 \times 10^{19} \text{ eV}$, are:

1. Scattering off cosmic microwave background photons limits the penetration depths of charged particles at these energies to distances $< 100 \text{ Mpc}$ [1, 2, 3];
2. the distribution of arrival directions of UHECRs does not seem to favor any known astrophysical sources within the GZK cutoff length;
3. it seems extremely difficult to devise sufficiently efficient astrophysical acceleration mechanisms which could accelerate particles to energies $E > E_{\text{GZK}}$, and at the same time overcome collisional and radiation losses.

The so called top-down models of UHECRs combine both problems by proposing that ultrahigh energy cosmic rays arise in the decay [4, 5, 6, 7, 8] or collisional annihilation [9, 10, 11] of superheavy dark matter particles. We will use both the acronym SHDM and WIMPZILLA\(^1\) for superheavy dark matter particles.

SHDM decay can arise through direct decay of relic particles (“WIMPZILLA” decay) or through the annihilation of superheavy relic bound states (“WIMPZILLIUM” decay), but the underlying decay

\(^1\) The word WIMPZILLA was coined by Kolb, Chung and Riotto in their investigations of possible origins of superheavy dark matter particles [12].

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mechanism plays no role for the predicted pattern of UHECR arrival directions. This pattern differs strongly from the anisotropy pattern predicted by collisional WIMPZILLA annihilation. The reason for the difference is that the anisotropy pattern predicted by decay models is proportional to the WIMPZILLA or WIMPZILLIUM density $n_X(x)$, and is dominated by the smooth background halo. Collisional annihilation, on the other hand, predicts that the anisotropy pattern should be proportional to $n_X^2(x)$, and is constrained by unitarity limits on annihilation cross sections. Therefore collisional annihilation can only work in dense cores of dark matter substructure in the galactic halo. These dense cores were denoted as WIMPZILLA stars [11]. As a consequence, the collisional annihilation scenario predicts a pointlike source distribution with increasing density towards the galactic center.

All modern acceleration (“bottom-up”) models for UHECR origin assume powerful extragalactic sources, and therefore predict that the pattern of observed arrival directions should not correlate with the galactic halo. The different patterns of UHECR arrival patterns predicted by all the different source models imply that a dedicated large statistics experiment like the Pierre Auger observatory can easily identify the correct model from its anisotropy signal.

Sec. 2 explains the origin of a mass window for the generation of relic superheavy dark matter particles during inflation. Sec. 3 summarizes and updates the calculation of the ultrahigh energy cosmic ray flux from collisional WIMPZILLA annihilation, and the origin of the unique pattern of arrival directions predicted by that model. In Sec. 4 we compare the different anisotropy signatures predicted by all contemporary proposals for the origin of ultrahigh energy cosmic rays, and Sec. 5 contains our conclusions.

2. Superheavy dark matter from inflation

Particle creation as a consequence of non-adiabatic expansion was discovered already in the late 1950s and 1960s, see [13] and references there. However, the effect was found to be negligible in radiation or dust dominated epochs, and therefore this mechanism for non-thermal particle creation was rediscovered and garnered much more interest only after the necessity for inflation was realized. The effect is usually considered in terms of the Bogolubov transformation between in and out vacua [12, 14, 15, 16, 17]. Particle creation during preheating after inflation can also arise as a consequence of a direct coupling between the inflaton and other matter fields [18, 19].

Here we will expand on a simple discussion given in [11] to see how particle production in an inflationary universe can be understood by studying the evolution equations of weakly coupled scalar fields in the expanding universe. The reasoning outlined here is not intended to compete in any way with the traditional operator methods to study particle production from spatial expansion, but it may provide a complementary and helpful view.

If interactions with other matter fields can be neglected, a scalar field in a Friedmann–Robertson–Walker background with metric

$$ds^2 = c^2 dt^2 + a^2(t) \left( \frac{dx^2}{k x^2} + \frac{d\theta^2}{1 - x^2 \sin^2 \theta} \right)$$

satisfies

$$\Box (x; t) + 3 \frac{\dot{a}(t)}{a(t)} (\dot{x}; t) + \frac{1}{a^2(t)} \partial_i (x; t) \partial^i (x; t) - \frac{1}{a^2(t)} \partial_i \partial^i (x; t) = 0; \quad (2)$$

and the corresponding energy density per unit of comoving volume is

$$\rho(x; t) = \frac{p}{a^3(t)} = \frac{a^3(t)}{2} \partial_i (x; t) \partial^i (x; t) + \frac{1}{a^2(t)} \partial_i (x; t) \partial^i (x; t)$$

$$\rho(x; t) = \frac{a^3(t)}{2} \partial_i (x; t) \partial^i (x; t) + \frac{1}{a^2(t)} \partial_i (x; t) \partial^i (x; t). \quad (3)$$
The violation of time translation invariance in (1) implies violation of energy conservation, of course:

\[ \square (x; t) \partial_t \Theta - \Theta \frac{1}{k \tau^2} \Theta - \Theta \frac{1}{k \tau} \Theta \]  

(4)

\[ \partial_t^2 (x; t) - \frac{a^2(t)}{a^2(t)} 3 m^2 \partial_x^2 (x; t) + \frac{1}{a^2(t)} \Theta \frac{1}{k \tau^2} \Theta (x; t) \Theta (x; t) : \]

A priori the sign of the expression on the right hand side is indefinite, e.g. a rapidly evolving field of low mass and with small spatial fluctuations loses energy during spatial expansion as long as it evolves rapidly enough. However, Eq. (2) tells us that spatial fluctuations (which should never have been large anyway for the Friedmann–Robertson–Walker ansatz to work) are soon negligible in the inflationary expanding universe \( a(t) / \exp(\Omega(t)) \). This leaves us with the simple equation

\[ \partial_t^2 (x; t) - 3 \frac{a^2(t)}{a^2(t)} + m^2 \frac{a^2(t)}{a^2(t)} \partial_x^2 (x; t) = 0; \]

(5)

Approximately constant \( H \) during inflation then yields for the time evolution of the comoving energy density

\[ \partial_t (x; t) = \frac{1}{2} a^3 (t) \partial_x^2 (x; t) \]

\[ + m^2 \frac{a^2(t)}{a^2(t)} \partial_x^2 (x; t) + \frac{1}{a^2(t)} \Theta \frac{1}{k \tau^2} \Theta (x; t) \Theta (x; t) \]

This implies a growing mode in the comoving energy density of weakly coupled states with \( m < 1 \times 10^{12} \) GeV. What is special about the superheavy particles is that their comoving energy density is conserved after inflation, because the behavior of massive \( m > 1 \) weakly coupled states in the subsequent radiation and dust dominated backgrounds preserves their energy. The asymptotic solution for weakly coupled massive states with \( m > 1 \) in such a background yields (with \( \gamma = 3 \) for dust, \( \gamma = 4 \) for radiation)

\[ \partial_t (x; t) = \frac{3}{2} a^3 (t) \cos (m \gamma t + \gamma); \]

\[ \partial_t (x; t) = a^3 (t) \frac{e^{\gamma t}}{\gamma}; \]

and this implies in particular that the comoving density of massive particles freezes out at the end of inflation \( t' \approx 10^{36} \) s if

\[ m > 1 \times 10^{12} \) GeV:

These considerations indicate a mass window for direct gravitational production of superheavy relic particles during inflation

\[ 10^{12} \) GeV < m < 10^{14} \) GeV:

After inflation intrinsically unstable matter of mass \( M \) will decay on time scales \( M_{\text{Planck}}^2 = M^3 \), where the upper bound assumes that the particles couple to their decay products at least with gravitational strength. This means that intrinsically unstable superheavy particles should not be relic particles. This difficulty has motivated the collisional annihilation scenario for ultrahigh energy cosmic rays from superheavy dark matter [9], because the unitarity limit on reaction cross sections

\[ \frac{4}{M_{\text{Planck}}^2} \]

implies that superheavy dark matter without direct decay channels will still be around.
3. Calculation of the flux

We consider decay or annihilation of superheavy dark matter particles of mass $M_X = 10^{12}$ GeV. The spectral fluxes at our location $r$ from decay or collisional annihilation of the dark matter particles of density $n_X (r)$ are then

$$j_\beta (E) = \frac{dN (E; M_X)}{dE} \frac{Z}{d^3r} \frac{1}{4} \mathcal{J} \frac{n_X (r)}{d},$$

(7)

and

$$j_\alpha (E) = \frac{dN (E; 2M_X)}{dE} \frac{Z}{d^3r} \frac{1}{16} \mathcal{J} \frac{n_X (r)^2 h \alpha v_i}{r};$$

(8)

respectively. Here $dN (E; E_{in})$ is the number of particles in the energy interval $[E; E + dE]$ emerging from a decay or annihilation event of initial energy $E_{in}$. $dN (E; E_{in}) = dE$ is related to fragmentation functions via

$$\frac{dN (E; E_{in})}{dE} = N \frac{\mathcal{F} (\kappa; E_{in})}{\mathcal{F} (\kappa; E_{in})} \frac{dE}{dE_{in}} = \frac{1}{\mathcal{F} (\kappa; E_{in})} \frac{\mathcal{F} (\kappa; E_{in})}{dE} \mathcal{F} ($

where $N$ is the number of particles in the energy interval $[E; E + dE]$ emerging from a decay or annihilation event of initial energy $E_{in}$. The factor in Eq. (8) equals 4 if the $X$-particles are Majorana particles, and 1 otherwise.

N-body simulations predict that usually about $\rho_{cl} = 5\%$ of dark matter halos should exist in substructure. Therefore in the decay models the ultrahigh energy cosmic ray flux will be dominated by the smooth background halo. Evaluating (7) e.g. for a Navarro-Frenk-White halo [20]

$$n_X (r) = 4n_X (r_s) r_s^3 = r (r + r_s)^2$$

yields

$$j_\beta (E) = \frac{4}{M_X^2} \frac{dN (E; 2M_X)}{dE} \frac{Z}{d^3r} \frac{r_s^3}{r^2} \frac{1}{r^2} \ln \frac{r_s}{r};$$

(9)

The scale radius $r_s$ for the Milky Way is not well known, but for the whole range of say $5 \text{ kpc}$ to $50 \text{ kpc}$ comparison between (9) and the ultrahigh energy cosmic ray flux from AGASA [21] yields that decaying superheavy dark matter should only make a small contribution to the galactic dark matter density. Of course, the problem is to explain a lifetime $\alpha 10^{17}$ s for unstable superheavy dark matter.

Equation (8) can also be evaluated analytically for a Navarro-Frenk-White halo, but the unitarity limit for s-wave annihilation

$$h \alpha v_i = \frac{4}{M_X^2} \frac{10^{-43} \text{ m}^3 \text{s}^{-1}}{\text{G eV}} \frac{M_X}{10^{12}} \frac{\text{100 km/s}}{v} \approx 1;$$

(10)

implies that any ultrahigh energy cosmic ray flux from collisional annihilation in the background halo is negligible. Therefore collisional WIMPZILLA annihilation can only make a noticeable contribution to the ultrahigh energy cosmic ray flux if it originates in dense cores of dark matter subclumps of the galactic halo [9]. These dense cores were denoted as WIMPZILLA stars in [11], and a simplified estimate of the cosmic ray flux from WIMPZILLA stars yields

$$j_\alpha (E) = \frac{N_{\text{cl-core}}}{16} \frac{dN (E; 2M_X)}{dE} n_X h \alpha v_i, \quad \frac{dN_{\text{cl-halo}}}{dE} \frac{n_X h \alpha v_i}{16} \frac{d^2M_X}{d^2M} \frac{dN (E; 2M_X)}{dE} n_X h \alpha v_i;$$

(11)

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Here $d^2 = r_\star^2$ is a mean inverse distance squared for our separation from galactic WIMPZILLA stars. In our estimate in [11] we had used $d' \approx 10$ kpc, which seems reasonable: e.g. our inverse mean distance squared to visible galactic substructures, the globular clusters, corresponds to $d = 7.8$ kpc.

We have parametrized the unknown annihilation cross section already in terms of the unitarity bound (10). Now we would like to compare e.g. with the UHE cosmic ray spectrum in Ref. [9], Fig. 1 (note that the cross section stated there would only be required for collisional annihilation in the smooth background halo and does not apply to annihilation in dark matter subclump cores). For the comparison we parametrize the core density $n_X$ of WIMPZILLA stars in terms of the solar density

$$n_X = \frac{\frac{6}{5} \times 10^{12} \text{ GeV}}{10^{37} \text{ m}^3} = 7.89 \times 10^7 \text{ m}^{-3};$$

This yields a flux at $10^{11}$ GeV of order

$$E^3 j(E)_{E = 10^{11} \text{ GeV}} = 5 \times 74 \times 10^{25} \text{ eV}^2 \text{ m}^{-2} \text{ s}^{-1} \text{ cm}^{-2} \frac{f_{\text{cl}}}{0.05} \frac{M_{\text{halo}}}{10^{12} \text{ M}_\odot} \frac{7.8 \text{ kpc}}{d} \times 10^{-3},$$

This complies with the spectral fit for the flux per solid angle in Ref. [9], Fig. 1, if $\langle s \rangle < 1$, as would be expected for consistency of the model: If the WIMPZILLAS are not Majorana particles ($= 1$) the required value for the fit is $\langle s \rangle = 9.8 \times 10^4$, and otherwise the required value would be $\langle s \rangle = 2.5 \times 10^4$.

### 4. Expected anisotropy patterns beyond $20$ EeV

Fits of fragmentation functions to the ultrahigh energy cosmic ray spectrum indicate that in the collisional annihilation scenario cosmic rays above $20$ EeV should be dominated by the fragmentation products of WIMPZILLA annihilation [9]. Therefore the expected anisotropy patterns discussed in this section only apply in this energy range.

The purpose of this section is to emphasize that the anisotropy pattern observed by the Pierre Auger observatory above $20$ EeV will provide a crucial direct test of the different proposals for the origin of ultrahigh energy cosmic rays: Bottom-up acceleration of charged particles in AGNs (see e.g. [22]) or gamma ray bursts [23], ultrahigh energy neutrinos travelling over cosmological distances and creating Z-bursts [24], WIMPZILLA or WIMPZILLIUM decay [4, 5, 6, 7, 8], or collisional annihilation in WIMPZILLA stars [9, 11].

| Origin of UHECRs                  | Expected anisotropy pattern                                      |
|-----------------------------------|------------------------------------------------------------------|
| Collisional annihilation in WIMPZILLA stars | About 1000 pointlike sources with increasing density towards the galactic center. No correlation with galactic SNRs. |
| WIMPZILLA or WIMPZILLIUM decay   | Dominated by uniform increase towards galactic center.           |
| Z-bursts                         | Approximately isotropic distribution with only weak correlation to structure within 150 Mpc. |
| Bottom-up acceleration           | Correlation with local superstructure within 150 Mpc.           |
Once fully operational, the Pierre Auger observatory should see more than 300 events per year with energies above 40 EeV. If the collisional annihilation scenario is correct, the observatory should see a large number of multiplets within its angular resolution, with increasing density towards the galactic center.

5. Conclusions

Collisional annihilation of superheavy dark matter particles as a source model for ultrahigh energy cosmic rays has the advantage of naturally explaining the absence of a GZK cutoff in the spectrum without correlation to local AGNs, without the need of postulating an extremely powerful and efficient acceleration mechanism, and without the need to explain extremely long lifetimes of intrinsically unstable particles. It has the disadvantage of having to postulate formation of a few relatively dense cores of dark matter subhalos or subhalo remnants.

The two different top-down scenarios of decay or collisional annihilation imply qualitatively different anisotropy signals in cosmic ray arrival directions, and these also differ from the anisotropy signals predicted by the various bottom-up scenarios. What constitutes a statistically significant dataset to confirm or reject the different anisotropy patterns depends on the different patterns, of course. However, for the collisional annihilation scenario the Pierre Auger observatory should see a large number of multiplets within its angular resolution already after about two years of full operation, because the UHECRs should arise from a limited number of pointlike sources in our galactic halo. Based on current particle physics extrapolations for chemical composition of cosmic rays to very high energies, bottom-up acceleration scenarios seem much more popular in the cosmic ray community. However, collisional WIMPZILLA annihilation is not an overly speculative theory, and based on its expected anisotropy pattern it will be confirmed or rejected in a very short time frame. It would therefore seem prudent to await what the Pierre Auger observatory will tell us about patterns of UHE cosmic ray arrival directions before jumping to any conclusions about the validity of different models.

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